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MATERIALS FOR POTASSIUM LUBRICATED JOURNAL BEARINGS

Quarterly Progress Report No. 9
Quarter Ending July 22, 1965

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MISSILE AND SPACE DIVISION
GENERAL  ELECTRIC
CINCINNATI, OHIO 45215

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ERRATA

MATERIALS FOR POTASSIUM LUBRICATED JOURNAL BEARINGS
QUARTERLY PROGRESS REPORT NO. 9
PERIOD: APRIL 22, 1965 to JULY 22, 1965

Page 2, paragraph 3, line 6: Reference for Coffin (4, 5) should be Coffin (9, 10)

Page 2, paragraph 3, line 11: Reference (6) should be (11)

Page 3, paragraph 2, line 5: Delete Sentence. At the end of the 1000-hour exposure, the chamber pressure was 3.4×10^{-9} torr.

Page 8, paragraph 3, line 15: Pressure of 1.4×10^{-9} torr should be changed to 1.4×10^{-6} torr.

Page 25, add the following references

⁹ Coffin, L. F., Jr., "Theory and Application of Sliding Contact of Metals in Sodium." Report KAPL-828, Knolls Atomic Power Laboratory, General Electric Company, October 1955.

¹⁰ Zeman, K. P., Young, W. R., and Coffin, L. F., Jr., "Friction and Wear of Refractory Compounds", Report 59GC-23, General Electric Company, May 1959.

¹¹ AiResearch Manufacturing Company of Arizona, Quarterly Technical Progress Report for Period Ending September 30, 1965, SNAP 50/SPUR Contract AF33(615)-2289 BPSN: 5(6399-675A) 63409124, ADS-5152-R4, p 7.

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Quarterly Progress Report No. 9

Covering the Period

April 22, 1965 to July 22, 1965

Edited by

R. G. Frank
Program Manager

Approved by

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Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Contract NAS 3-2534

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SPACE POWER AND PROPULSION SECTION
MISSILE AND SPACE DIVISION
GENERAL ELECTRIC COMPANY
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FOREWORD

The work described herein is being performed by the General Electric Company under the sponsorship of the National Aeronautics and Space Administration under Contract NAS 3-2534. Its purpose, as outlined in the contract, is to evaluate materials suitable for potassium lubricated journal bearing and shaft combinations for use in space system turbogenerators and, ultimately, to recommend those materials most appropriate for such employment.

R. G. Frank, Manager, Physical Metallurgy, Materials and Processes, is administering the program for the General Electric Company. L. B. Engel, Jr., T. F. Lyon, W. H. Hendrixson and B. L. Moor are directing the program investigations. The design for the friction and wear testers was executed by H. H. Ernst and B. L. Moor.

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I. INTRODUCTION

The program reviewed in this ninth quarterly report, covering activities from April 22, 1965 to July 22, 1965, is performed under the sponsorship of the National Aeronautics and Space Administration. Its purpose is to evaluate materials suitable for potassium lubricated journal bearing and shaft applications in space system turbogenerators operating over a 400° to 1600°F temperature range. The critical role of bearings in such systems demands the maximum reliability attainable within today's state-of-the-art. Achieving this reliability requires an interdisciplinary approach employing the best mechanical designs of journal bearings combined with the selection of the optimum materials to serve as the structural members. Satisfying this latter requirement constitutes the aim of this program.

A number of investigators have conducted studies in this field and their contributions have advanced the state-of-the-art considerably (Section VIII, Ref. 1). Although their work is significant, there are no common criteria for a comparison of the existing data. Therefore, establishing a unified approach to the development and evaluation of materials for potassium lubricated bearing application is deemed essential. The program involves a comprehensive investigation of material properties adjudged requisite to reliable journal bearing operation in the proposed environment. This includes: 1) corrosion testing of individual materials and potential bearing couples in potassium liquid and vapor, 2) determination of hot hardness, hot compressive strength, modulus of elasticity, thermal expansion and dimensional stability characteristics, 3) wetting tests by potassium and 4) friction and wear measurements of selected bearing couples in high vacuum and in liquid potassium.

In cooperation with the cognizant NASA Technical Manager, 14 candidate materials were selected (Table I) from a compilation of existing data on available materials. The materials reviewed fall into four broad categories:

- Superalloys and refractory alloys with and without surface treatment
- Commercial metal bonded carbides
- Refractory compounds such as stable oxides, carbides, borides and nitrides
- Cermets based on the refractory metals and stable carbides

Each material is procured from appropriate suppliers to mutually acceptable specifications and subsequently is subjected to chemical, physical and metallurgical analyses to document its characteristics before utilization in the program. After the documentation of processes and properties, the candidate materials undergo corrosion, dimensional stability, thermal expansion, compression and hot hardness testing. Considering the bearing material requirements and the information obtained

on the candidate bearing materials which were subject to both potassium and non-potassium testing, seven materials combinations listed below were selected in co-operation with the NASA Technical Manager. Potassium corrosion and wetting tests and friction and wear measurements in high vacuum and liquid potassium will proceed with these combinations.

<u>Rotating Rider</u>	<u>Stationary Rider</u>
*1. Grade 7178	Mo-TZM
2. Mo-TZM	Grade 7178
*3. Grade 7178	Grade 7178
4. Carboloy 907	Mo-TZM
5. Carboloy 907	Carboloy 907
6. TiC+10%Cb	Mo-TZM
*7. TiC+10%Cb	TiC+10%Cb

Those materials combinations marked with an asterick (*) were selected for friction and wear testing in both liquid potassium and high vacuum. Where significant differences in hardness exist, the softer material, i.e., Mo-TZM alloy, was selected as the rider material (stationary specimen) to facilitate wear-in during testing in liquid potassium. Couple No. 2 was selected to determine what affect a hard rider material would have on the wear pattern of a soft disc material in comparison with the reverse combination.

The decision to place considerable emphasis on the refractory metal bonded carbides was based on their excellent stability at the higher temperatures. Also, it was elected to test the hard carbide materials against themselves in order to obtain a direct comparison of the friction and wear behavior of hard/hard combinations vs hard/soft combinations where Mo-TZM alloy is one material in a pair. From investigations conducted by Coffin (4,5), it was concluded that generally it is desirable to have one of the materials harder than the other in order to facilitate wear-in of the couple. If both materials are hard and brittle, the surface asperities on the weaker material can fracture and the resultant debris could cause severe surface damage by abrasion. However, recent friction and wear tests and full scale bearing tests conducted elsewhere (6), using liquid potassium as a lubricant, have indicated superior performance of hard/hard combinations over hard/soft combinations because of the tendency of wear debris from the hard material to become imbedded in the soft material of hard/soft combinations and possibly resulting in a cutting action.

The ultimate product of this program will be a recommendation, substantiated with complete documentation, of the material or materials which have the greatest potential for use in alkali metal journal bearings in high speed, high temperature rotating machinery for space applications. Hopefully, the results will indicate the future course of alloy or material development specifically designed for alkali metal lubricated journal bearing and shaft combinations.

II. SUMMARY

During the ninth quarter of this program the topics abstracted below were covered and the results interpretively presented in this report.

Nine 1000-hour isothermal capsule corrosion tests were conducted in vacuum (10^{-9} torr) at 800°, 1200° and 1600°F to evaluate the compatibility of selected candidate bearing material combinations in a potassium/Cb-1Zr alloy system. The material combinations tested were Mo-TZM alloy vs Carboloy 907, Mo-TZM alloy vs Grade 7178 and Mo-TZM alloy vs TiC+10%Cb. At the end of the 1000-hour exposure, the chamber pressure was 3.4×10^{-9} torr. The oxygen content of the potassium used to fill the capsules was analyzed to be less than 11 ppm as determined by the mercury amalgamation technique.

Metallographic examination of all specimens exposed individually to potassium for 1000 hours at 1600°F has been completed. No significant changes in microstructure were observed in any of the following materials as a result of the exposure to potassium liquid or vapor: Mo-TZM alloy, unalloyed tungsten, TiC+10%Mo, TiC+10%Cb, Lucalox (Al_2O_3) and TiB_2 ; slight surface attack to depths of 0.0002 to 0.0007 inch were observed in specimens of Carboloy 907, Carboloy 999, TiC and TiC+5%W; some surface roughening was apparent with the K601 specimens exposed to potassium liquid; and a general chemical reaction between Zircoa 1027 and potassium was observed changing the color of the specimens from light yellow to dark grey throughout the entire cross section. Although no corrosion reactions were evident for the Grade 7178 and Star J materials, morphological changes due to the thermal exposure were observed. Solution/aging reactions occurred in the Star J material and possible coalescence of the eutectic phase was observed in Grade 7178.

Visual examination and dimensional and weight data obtained from specimens exposed to potassium at 800° and 1200°F generally showed significantly less change than specimens exposed for 1000 hours at 1600°F.

Operational checkout tests for the high vacuum friction and wear tester were completed and the first series of tests were conducted at temperatures to 1200°F, surface speeds of 500 SFM and loads up to 90% of the 0.2% CYS or UCS of the test material. Chamber pressures were maintained in the 10^{-9} to 10^{-10} torr range using standard, unlubricated MRC 7207 angular contact ball bearings in the main shaft. In the checkout tests, shaft speeds of 5000 RPM and specimen temperatures of 1600°F were achieved without difficulty. However, indications are that modification of the test facility by reducing the spring constant of the loading arm bellows and the use of force pickups that are more sensitive in the lower load range will improve the test results to be obtained for those materials which require testing at very light loads. Overall, no major modifications of the test facility appear necessary.

The Cb-1Zr alloy sheathed, BN insulated conductive immersion heater assembly was fabricated successfully and tests for leaks and electrical continuity indicated the heater assembly to be suitable for installation in the test rig. Compatibility tests of Cb-1Zr alloy sheathed, Al_2O_3 insulated heater were conducted in vacuum (10^{-9} torr) for 118 hours at 1600°F . The breakdown voltage of the Al_2O_3 (99.5% Al_2O_3) insulated heater was found to be 100 volts after the 118-hour exposure. Similar tests for the BN (99.5%BN) insulated heater indicated breakdown voltages in excess of 3000 volts. All heaters successfully withstood an applied potential of 2100 volts between the Nichrome elements and the Cb-1Zr alloy sheath prior to conducting the 118-hour compatibility test.

Assembly of the potassium wetting facility was completed and after a vacuum bakeout, a chamber pressure of 7×10^{-10} torr was achieved with the system at room temperature.

III. PROCUREMENT OF CANDIDATE JOURNAL BEARING MATERIAL COMBINATIONS FOR CORROSION AND FRICTION AND WEAR TESTING

The delivery status of the Mo-TZM alloy, Carboloy 907, Grade 7178 and TiC+10%Cb test specimens required for corrosion and friction and wear testing of selected candidate journal bearing material combinations is given in Table II. The delay in the delivery of the remaining Grade 7178 and TiC+10%Cb specimens is the result of a strike at the vendors' plant.

The cleaning, visual and penetrant inspection and weight and surface finish measurements of the friction and wear specimens are in progress and the pretest data will be compiled in the test specimen control sheet shown in Appendix I and the pertinent data will be reported with the results of each test.

IV. TEST FACILITIES

A. Friction and Wear in Liquid Potassium

Sump Heater

Based on the results of the 123-hour compatibility tests in high vacuum at 1600^oF (2), the vendor of the conductive immersion heating elements was instructed to proceed with the fabrication of 14 additional Cb-1Zr alloy sheathed heating elements having Al₂O₃* cores, BN** powder insulation and BN*** end plugs. The Al₂O₃ cores and the BN powder and end plugs were outgassed for one hour in a vacuum of 5×10^{-6} torr; the Al₂O₃ cores were outgassed at a temperature of 2200^oF and the BN powder and end plugs were outgassed at a temperature of 2800^oF. After outgassing, the material was sealed under argon in plastic bags and shipped to the vendor for fabrication. No apparent problems were experienced by the vendor in the fabrication of the heaters and upon receipt of the heaters they were submitted to quality assurance testing which consisted of fluorescent penetrant and radiographic inspection and resistance measurements across the BN insulation. Each heater was radiographed in two directions at 90^o intervals to determine the uniformity of the spacing of the Nichrome heating wires with respect to each other and to the Cb-1Zr alloy sheath. The resistance of the BN insulation between the heater wire and the sheath was measured by a megohmmeter at a potential of 500 volts. The results of the quality assurance tests are summarized in Table III.

Although radiographic examination of the heaters revealed no voids in the swaged ceramic insulators, 100% density is difficult to achieve and the natural porosity that exists in the ceramics is a source for outgassing of entrapped air during operation of the heater. However, in all probability the total amount of reactive gas entrapped in the ceramics due to the swaging of the heater in air would represent less than a 100 ppm increase in oxygen/nitrogen should all of the gas react with the Cb-1Zr alloy sheath.

Since facilities were not available to perform the compaction and final swaging operations in an inert atmosphere and the amount of possible contamination appeared to be small, no precautions were taken to prevent entrapment of air.

* Saxonburg Ceramics, Saxonburg, Pa., Grade ST-61, >99.5% Al₂O₃; Analysis: MgO, 0.02%; SiO₂, 0.09%; Fe₂O₃, 0.06%; Cr₂O₃, 0.002%; TiO₂, 0.003%; CaO, 0.05%; C, 0.035% S, 0.002%; B, <10 ppm; Cd, <3 ppm; Hf, <80 ppm.

** Carborundum Electronics Div., Latrobe, Pa., Grade HPC, >99.5% BN; Analysis Maximum: Cl, 0.01%; SO₄, 0.0005%; NH₃, 0.0005%; B₂O₃, 0.2%; Al, 0.1% Si, 0.05%; Fe, 0.1%; Mg, 0.03%; Ca, 0.1%; Na, 0.1%; Cr, 0.1%; Mn, 0.005%; Ti, 0.1%.

*** Carborundum Electronics Div., Latrobe, Pa., Grade A, 97% BN; Typical Analysis: B₂O₃, 2.4%; Alkali Earth Oxides, 0.1%; Al₂O₃, 0.2%; SiO₂, 0.2%; C, 0.008%.

Also, compatibility tests conducted with BN/Al₂O₃ insulated heaters at temperatures of 1600°F for a period of 123 hours and reported in Quarterly Progress Report No. 8 (2) (page 63) showed no oxygen contamination of the inner 0.020-inch thick layer of the Cb-1Zr alloy sheath. However, for critical alkali metal applications requiring long time service at temperatures in excess of 1600°F, it may be desirable to consider carrying out the heater fabrication operations under an inert cover gas.

Seven heating elements were selected for fabrication, prepared for welding, and cleaned with acetone, and the remaining components of the sump heater, i.e., Cb-1Zr alloy torus, Cb-1Zr alloy conduit, Cb-1Zr alloy/Type 304SS bimetal joint and nickel lead wires, were fabricated. Subsequently, the entire heater assembly for the potassium sump was completed and successfully tested for electrical continuity. The completed heater assembly is shown in Figure 1.

The Al₂O₃ cores, powder**** and end plugs for the Cb-1Zr alloy sheathed, Al₂O₃ insulated heating elements were received from the vendor and were outgassed for one hour at 2200°F in a vacuum of about 1×10^{-5} torr. Subsequently, they were sealed in plastic bags under argon and returned to the vendor for fabrication of the trial heaters. Two heaters were fabricated in the same manner as were the BN insulated heaters and upon their receipt at General Electric were found to have heater wire resistances of 22 ohms and insulation resistance of 200,000 ohms each. Prior to installing the heaters in the high vacuum chamber, the Cb-1Zr alloy sheaths were pickled in a 20%HF-20%HNO₃-60%H₂O solution. After cleaning, a Pt vs Pt+10%Rh thermocouple was spot welded to the outer surface of the sheath at about 1/3 of the length from the sealed end of the heater and the heaters were connected to the electrical power leads in parallel. The test chamber was evacuated, baked out for 16 hours at 650°F and subsequently evacuated to a pressure of 2.5×10^{-9} torr. The power was turned on and the heaters were brought up to a temperature of 1600°F (47 volts, 2.8 amps) with the pressure never exceeding 1.4×10^{-9} torr. Because of current leakage through the heater insulation, the thermocouple readings were found to be in error and temperature measurements had to be made with an optical pyrometer. The heaters were held at the 1600°F test temperature for 118 hours; the pressure at the time that the test was terminated was 1.4×10^{-9} torr. The power generated per heater was 7.76 KW-hour (compared to 9.23 KW-hour for the heaters having BN insulation).

After the test, the thermocouples were re-calibrated and found to read -0.2°F and -3.5°F from true temperature. The heater's wire resistance was measured and found to be unchanged at 22 ohms. However, the insulation resistance of the heaters could not be determined. The heaters acted like capacitors in that they would accept a charge of one volt which would gradually decay. The breakdown voltage, at which level current would flow through the insulation for the heater, was determined for heater J3NX13A-1 and found to be as low as 100 volts DC. This compares to DC breakdown voltages measured with BN insulated heaters in excess of 3000 volts (2) after a similar 1600°F compatibility test. This destructive test was not applied to Al₂O₃ insulated heater J3NX13A-2 so that additional compatibility tests could be conducted at 1800°F along with a heater having BN insulation.

**** Norton Company, Wooster, Mass., Grade Alumdum Type 38; Typical Analysis:
Al₂O₃, 99.49%; SiO₂, 0.05%; Fe₂O₃, 0.10%; TiO₂, 0.01%; Na₂O, 0.35%.

All heaters successfully withstood an applied potential of 2100 volts between the Nichrome heating elements and the Cb-1Zr alloy sheath.

B. Friction and Wear in High Vacuum

After the tare-weight and pickup force tests were completed (2), the high vacuum friction tester (HVFT) was disassembled and thoroughly cleaned. The shaft and all rotating components were installed in the same positions in which they were balanced. Standard Type 7207 angular contact ball bearings, cleaned of all traces of oil and lubricated with MoS₂ were installed in the bearing housing. The specimen heater was installed into the vacuum facility. Guides were fabricated to center the HVFT above the main vacuum flange in order to prevent damage to the specimen heater and shielding. After seating the HVFT on the main flange, the heater was tested for electrical continuity, seating of the heater shield-cap was assured, the shaft was rotated satisfactorily by hand and the loading arms were installed.

The detailed assembly instructions listed below were followed in the installation of the critical subassemblies:

HVFT - AI1	"High Vacuum Friction Tester SK56131-250 - Subassembly of H28 Bearing Housing SK-56131-251"
HVFT - AI2	"High Vacuum Friction Tester SK-56131-250 - Assembly of H44 Shaft (SK-56131-262G2) in H35 Vacuum Chamber (SK-56131-275)"
HVFT - AI3	"High Vacuum Friction Tester SK-56131-250 - Subassembly of Loading Arms H64 Specimen Holder Assembly (119C2844)"

Instrumentation was secured in the following locations:

Vibration Pickups (See Figures 2 - 5 for Calibration)

<u>Pickup No.</u>	<u>Location</u>	<u>Readout Channel</u>
4769	Upper bearing, horizontal	1
2898	Upper bearing, vertical	4
5019	Lower bearing, horizontal	3
4772	Lower bearing, vertical	2

Thermocouples

<u>Thermocouple No.</u>	<u>Location</u>
1 and 2	Loading Arm No. 1

3 and 4	Loading Arm No. 4
5 and 6	Loading Arm No. 3
7 and 8	Loading Arm No. 2
9	Diaphragm
10	Outside HVFT, above arm pad cooling chamber
11	Outside HVFT, below arm pad cooling chamber
12	Outside HVFT, on main flange
13 and 14	Upper bearing
15 and 16	Lower bearing

HVFT Operational Checkout Tests

The HVFT was assembled as shown in Figure 6. No hemispherical rider specimens were installed in the loading arms and no cooling coils were installed inside the vacuum chamber. Otherwise, the tester was assembled as it would be during actual testing. The four Mo-TZM alloy disc specimens were included in this assembly to prevent their holding screws, nuts, and washers from moving and affecting the balance of the shaft assembly during the rotational tests. Also, their presence also duplicated the heat transfer conditions of actual testing.

The results of the operational checkout tests are presented below:

1. The capability of the magnetic pickup to measure rotational speed of the main shaft from 0 - 5000 RPM was established.
2. A calibration curve for the motor control setting vs the rotational speed of the main shaft was developed to allow an accurate setting of speed even if the magnetic pickup and EPUT meter should fail or give false readings, Figure 7.
3. The speed capability of the shaft assembly rotating in a high vacuum and utilizing commercial bearings was established at rotational speeds of up to 5000 RPM. The level of vibration was considered satisfactory, Figure 8. The diaphragm between the magnets reached a maximum temperature of 180°F due to the rotation of the magnets.
4. A curve correlating the pressure indicated by the ion pump current vs the ionization gauge located in the chamber was developed, Figure 9.

5. The capability of the specimen heater to heat specimens to 1600°F without exceeding the temperature limits established for the bearings and other critical components of the tester was established; component temperatures remained below 120°F when the rider specimen temperatures reached 1780°F, Figure 10. However, the temperature differential between the rider specimens was greater than desired and as a result will restrict testing to one specimen at a time. This temperature differential is caused by heater geometry, e.g., the presence of the view-port hole.

Voltage, current, and power characteristics of the heater at two different levels of supply voltage are presented in Figure 11. The 12 volt transformer will be used in future testing.

6. The absence of any interference between static and rotating components at the maximum test temperature of 1600°F was established.
7. The efficiency of the high vacuum friction tester housing bakeout heaters was proved after external insulation was added. The effectiveness of the air cooling channels was satisfactory.
8. Difficulty was experienced in maintaining pressures lower than the 10^{-6} torr range during the specimen heater test. This was attributed primarily to a leak in the main flange of the tester which could not be corrected without terminating the heater tests. The previous achievement of a 10^{-10} torr pressure was considered to be satisfactory proof of the vacuum capability of the system.

Upon completion of the operational checkout tests, the bearings were checked by rotating the shaft and found to be acceptable for future use. They will be left in the high vacuum friction tester during specimen testing at speeds of 500 SFM in order to preserve the three sets of gold and silver plated bearings for high speed use.

Subsequently, the high vacuum friction tester was prepared for installation of specimens for the first friction and wear tests.

C. Potassium Wetting

The potassium wetting apparatus, as described in Quarterly Progress Report No. 8 (2), was assembled with a Mo-TZM alloy specimen in position. Prior to installing the specimen, the upper surface was given a metallographic polish through 0.05 micron alumina on a vibratory polisher. The auxiliary bakeout heaters were installed and the thermocouples to monitor bakeout temperatures were attached at various locations on the facility. Subsequently, the system was baked out and a pressure of 7×10^{-10} torr was achieved with the system at room temperature.

Since the test chamber must be heated and isolated from the pump during the wetting measurements, several tests were performed to determine the pressure rise rate in the system with the main test chamber heater and the getter-ion pump off. Such a measurement shows the approximate pressure at which the actual wetting measurements will be performed. These tests have shown a pressure rise rate of 5.6×10^{-6} torr per hour with the main test chamber at about 310°F and a pressure rise rate of 7.0×10^{-5} torr per hour with the chamber at about 410°F . The actual wetting measurements will extend over several hours and thus the chamber pressures will be in the 10^{-5} torr range at 310°F and in the 10^{-4} torr range for tests at 410°F . It is possible that these pressure rise rates could be considerably reduced by additional bakeout of the system at high temperatures.

The wetting measurements have been delayed by difficulties encountered in the operation of the ultra-high vacuum valves. However, at the present time, it appears that further problems with these valves can be prevented by assuring that the sealing ball and the seat are of proper dimensions and that the sealing surface has a good surface finish.

A sample of the potassium was transferred from the titanium-lined hot trap into a 18-inch length of 0.5-inch OD x 0.020-inch thick wall tubing for subsequent transfer to the potassium wetting facility. Purification of the potassium was described in Quarterly Progress Report No. 7 (3). Half of the 18-inch long sample was utilized for chemical analyses for oxygen by amalgamation techniques (helium cover gas) and for metallic impurities by spectrographic techniques. Duplicate oxygen analyses showed the oxygen content to be 6.1 and 7.3 ppm. Metallic impurities were found to be less than the detectable standards.

METALLIC IMPURITIES (1,2) IN POTASSIUM, PPM

Lab																
No.	<u>Al</u>	<u>Ag</u>	<u>B</u>	<u>Be</u>	<u>Ca</u>	<u>Cb</u>	<u>Co</u>	<u>Cr</u>	<u>Cu</u>	<u>Fe</u>	<u>Mg</u>	<u>Mn</u>	<u>Mo</u>	<u>Na</u>	<u>Ni</u>	<u>Si</u>
201	<1	<1	<25	<1	1	<1	<1	<1	<1	1	<1	<1	<1	1	<1	1
						<u>Sn</u>	<u>Ti</u>	<u>V</u>	<u>Zr</u>	<u>Pb</u>						
						<5	<1	<5	<5	<1						

(1) Metallic Impurities in KCl Analyzed by Spectrographic Techniques.

(2) Samples Cast Inside EB Tank Under Vacuum.

A 4-inch section of the remaining sample, containing approximately 10 grams of potassium, will be inserted into the potassium reservoir of the wetting test facility. The transfer will be made under high-purity argon in a glove box capable of being evacuated to a pressure of 10^{-6} torr.

V. TEST PROGRAM

A. Corrosion

In order to evaluate the compatibility of the candidate bearing material combinations in a Cb-1Zr alloy/potassium system, additional 1000-hour isothermal capsule tests were conducted with the following three material combinations at 800°, 1200° and 1600°F:

- Mo-TZM alloy vs Carboloy 907
- Mo-TZM alloy vs Grade 7178
- Mo-TZM alloy vs TiC+10%Cb

The capsule testing was conducted in the same facilities and, with one exception used the same techniques and procedures as were used for the previous capsule testing of individual materials (4). The one exception is that two specimens, one specimen of each material, were tested in both the liquid and vapor regions of the Cb-1Zr alloy capsule. In this regard, the Cb-1Zr alloy wire basket that contains the test specimens was enlarged to accommodate the two specimens with the specimens being separated from one another at the top and bottom by a 0.020-inch diameter Cb-1Zr alloy wire attached to the cross bars of the basket, Figure 12.

Nine Cb-1Zr alloy capsules, together with the 36 selected corrosion test specimens, were prepared, filled with high purity potassium and sealed under vacuum in the same manner as described previously in Quarterly Progress Report No. 5 (5). In addition, four Cb-1Zr alloy capsules, two containing TiC+10%Mo specimens and two containing TiB₂ specimens were filled with high purity potassium and sealed under vacuum. These four capsules complete the testing of individual candidate bearing materials at 800° and 1200°F.

Samples of the potassium which were obtained during the filling of the three sets of corrosion capsules were analyzed for oxygen by the mercury amalgamation method. These results are given in Table IV. The results of spectrographic analyses for metallic elements of two samples taken during the filling of the capsules are shown in Table V.

After careful visual and radiographic examination, the 13 prepared capsule assemblies were placed on test in the same manner as that described in Quarterly Progress Reports No's 5 (5) and 6 (6). The chamber was sealed, evacuated to 6×10^{-7} torr and given a 24-hour bakeout at 400°F after which the pressure dropped to 5.2×10^{-8} torr. All three susceptors were brought to their respective test temperatures of 800°, 1200° and 1600°F simultaneously while the chamber pressure was maintained at less than 1×10^{-6} torr. Subsequently, the capsules were held at their respective test temperature for 1000 hours.

The chamber pressure at the time that the tests were terminated was 3.4×10^{-9} torr as measured by a Bayard-Alpert ionization gauge attached to the side of the chamber. After the susceptors had cooled, the chamber pressure dropped to 9.8×10^{-10} torr. The actual test temperatures are shown in Table VI.

The four capsules containing the individual candidate bearing materials, TiC+10%Cb and TiB₂, have been opened under argon, the potassium drained and the specimens cleaned by vacuum distillation in the manner described in Quarterly Progress Report No. 7 (3). Weight and dimensional measurements of the TiC+10%Mo and TiB₂ specimens tested at 1200°F were obtained and are reported in Table VII along with the pre-test data and the observed changes. Also, the weight and dimensional measurements of all the candidate bearing material test specimens tested individually at 800°F were compiled and the data are reported in Table VIII along with the pre-test data and the observed changes. The data were evaluated in the same manner as were the data obtained from the test specimens tested at 1600° (3) and 1200°F (2). A summary of the dimensional and weight changes observed in the specimens tested at 1600°, 1200° and 800°F for 1000 hours is presented in Table IX.

The weight losses of Carboloy 999 and Carboloy 907 specimens tested at 1600°F are attributed to the transfer of carbon from the specimens to the Cb-1Zr alloy capsule (2). Although the Carboloy specimens tested at 1200°F generally show a weight loss, the changes are significantly less than those observed for the specimens tested at 1600°F. Also, a slight dimensional growth was observed in the Carboloy 999 and Carboloy 907 specimens tested at 1200°F in contrast to negative changes in dimensions for the specimens tested at 1600°F. The positive dimensional changes of the Carboloy 907 specimen tested at 1600°F in liquid potassium is believed to be a surface reaction which resulted from an exposure to argon during the vacuum distillation cleaning after testing. The Carboloy specimens tested at 800°F show a slight dimensional growth and no negative weight changes.

The dimensional growth observed in the Lucalox (Al₂O₃) specimens tested at 1600°F is attributed to a surface reaction and the possible formation of KAlO₂ as was observed in compatibility studies at Battelle Memorial Institute (8). Corresponding weight increases also were noted with the Lucalox specimens tested at 1600°F. No apparent surface reactions occurred between the Lucalox specimens and potassium in the 1200° and 800°F tests and negligible changes in dimensions and weight were observed for the Lucalox (Al₂O₃) specimens tested at these temperatures.

The dimensional growth and weight increases observed for the Zircoa 1027 specimens tested at the 1600°, 1200° and 800°F are believed to be the result of phase changes of the monoclinic structure found to exist in the as-received material and chemical reactions during testing. It should be noted that the changes were significantly smaller at the lower test temperatures. In regard to the chemical reactions during testing, a distinct color change from light yellow to grey was observed throughout the specimens tested at 1600° and 1200°F. A similar color change was observed in the specimens tested at 800°F but only to a depth of 0.025 inch, Figure 13.

The weight losses observed in the Grade 7178 specimens are attributed to the transfer of carbon to the Cb-1Zr alloy capsule and the possibility of chipped edges and/or corners which were observed after testing. However, the magnitude of the change in weight suggest that significant transfer of carbon occurred only at the 1600°F test temperature.

The dimensional growth observed in the Star J specimens tested at 1600°F is believed to be the result of morphological changes due to aging reactions. These changes have been observed metallographically and are discussed later in this report. The weight losses observed in the specimens tested at 1600°F are attributed to carbon transfer (2). Generally, no significant dimensional changes were observed in the specimens tested at 1200° and 800°F; also the weight changes of these specimens are positive in contrast to the negative changes observed in the 1600°F test with the magnitudes of the weight changes that occurred at the lower temperature being considered insignificant.

A slight weight gain was observed in most of the TiB₂ specimens tested and is unexplainable at this time.

Other significant weight losses which were observed in various specimens may be all or partly caused by chipped edges and/or corners observed after testing and little significance is attached to these changes. It should be noted that Mo-TZM, unalloyed tungsten, TiC and the refractory metal bonded TiC specimens prove to have excellent stability in potassium at all test temperatures.

All of the test specimens exposed to potassium liquid and vapor for 1000 hours at 1200° and 800°F were examined visually and the major differences observed in the appearances of the specimens as compared to the appearance of the specimens tested at 1600°F are summarized in Tables X and XI, respectively. The visual appearance of all the remaining specimens were similar to those tested at 1600°F and reported in Table IX of Quarterly Progress Report No. 7 (3).

Metallographic examination of the specimens exposed to potassium liquid and vapor for 1000 hours at 1600°F has been completed. To illustrate the relative grain sizes of the 14 candidate materials, photomicrographs of all the materials are presented at a constant magnification of 250X. Additional photomicrographs of specific materials at higher magnifications are presented where appropriate.

No significant microstructural changes were observed in the specimens of the following materials which were exposed to potassium liquid and vapor at 1600°F: Mo-TZM alloy, Figure 14; unalloyed tungsten, Figure 15; TiC+10%Mo, Figure 16; TiC+10%Cb, Figure 17; Lucalox (Al₂O₃), Figure 18; and TiB₂, Figure 19.

Examination of the Carboloy 999 specimens shows what appears to be a corrosion reaction on the surface of the specimen exposed to potassium liquid to a depth of approximately 0.0004 inch and a surface roughening of the specimen exposed to potassium vapor to an extent of approximately 0.0002 inch, Figures 20 and 21. A similar attack was observed on the surface of the Carboloy Grade 907 specimens, Figures 22 and 23. However, the attack on the Carboloy 907 material exposed to

potassium liquid appears to be more severe than that observed in the Carboloy Grade 999 specimens, i.e., to a depth of approximately 0.0007 inch vs 0.0004 inch.

Examination of the Zircoa 1027 specimens revealed a reaction between the ZrO_2 , $\text{CaMgO-Al}_2\text{O}_3\text{-SiO}_2$ matrix and the potassium with what appears to be intergranular attack. This was evident in the specimens exposed to both liquid and vapor potassium, Figure 24. As observed visually, the colors of the Zircoa 1027 specimens changed from a light yellow or yellowish brown to a uniform dark grey throughout the entire cross section. The evaluation of the x-ray diffraction data for Zircoa 1027 currently is in progress in an effort to explain the changes observed metallographically and visually.

The K601 specimen exposed to liquid potassium only showed a general surface roughening and no change was observed in the specimen exposed to potassium vapor, Figure 25.

The TiC specimen exposed to liquid potassium exhibited surface roughening and very slight intergranular attack to a depth of less than 0.0002 inch, Figures 26 and 27. The specimen exposed to potassium vapor showed a very slight surface roughening. The TiC+5%W specimens exhibited similar attack as observed in the TiC specimens, Figures 28 and 29. Although the attack observed in the TiC+5%W specimen exposed to liquid potassium appears to be more severe than what was observed in the TiC specimen, i.e., a depth of 0.0004 inch vs 0.0002 inch, the TiC+5%W specimen exposed to potassium vapor showed only a very slight amount of attack or surface roughening. No significance is attached to the apparent voids which have been greatly accentuated during etching.

Although no serious surface attack was observed in the Grade 7178 specimens, Figure 30, the structure appears to be more coarse after the 1000-hour exposure at 1600°F. This is attributed to either agglomeration of the eutectic phase or inhomogeneity between specimens, Figure 31. It should be noted that the dark regions observed in the photomicrographs contained the eutectic phase of the Grade 7178 and was pulled out during polishing.

No significant surface attack was observed in either of the Star J alloy specimens, Figure 32. However, examination of the microstructure clearly reveals a morphological change due to aging reactions. The precipitation of M_{23}C_6 was observed in both specimens after exposure for 1000 hours at 1600°F, Figure 33. Also, the dark "Chinese Script", M_6C , appears to be going into solution and an unidentified phase that appears similar to the Cr_7C_3 needles is forming. Further investigation of the precipitation of the unidentified phase and the solutioning of the M_6C is in progress.

The metallographic preparation of the specimens exposed to potassium for 1000 hours at 1200°F has been completed and the evaluation is underway. Also, the specimens exposed to potassium for 1000 hours at 800°F have been sectioned for metallographic examination in the same manner as were the specimens tested at 1600°F (7) and metallographic preparation is in progress.

B. Friction and Wear in High Vacuum

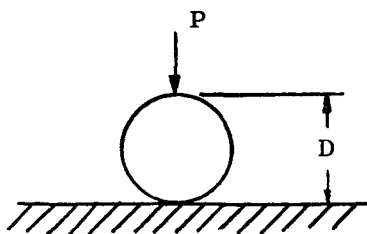
Test Plan

The test plan was revised to reflect the addition of detailed requirements that only could be established after the material combinations were selected. The revised test plan schedule for the high vacuum friction and wear test program is presented in Table XII; the identification of the material combinations corresponding to the pairs number in Table XII is given in Table XIII.

Because of the large spread in strength of the selected bearing materials, the basic premise of having one constant load, K , which would produce compressive stresses equal to 50% of the compressive yield strength of the weakest pair to be tested for all material pairs became impractical. As a result, two constant loads, K and H , were selected. It was necessary to establish the K load at a level to produce 90% of the 0.2% CYS in the Mo-TZM alloy specimen in the weakest pair because the loads required to achieve 50% of the 0.2% CYS of the Mo-TZM alloy specimen were too light for accurate measurement. The K load will be used for pairs 1, 2, 4 and 6. However, since this load produces immeasurably small wear on the harder pairs, a higher constant load H , the load required to achieve 75% of the UCS of pair 7, is to be used for pairs 3, 5 and 7.

The change in the level of the K load and information gained from preliminary test runs also made the basic premise of having a variable load, P_{90} , for each pair, equal to the load required to achieve 90% of the 0.2% CYS or UCS of the weakest material of that pair, impractical. For pairs 4 and 6, this load was so nearly the same as the K load (because Mo-TZM alloy is a member of each of the pairs 1, 2, 4 and 6) that the tests essentially would be a repetition of the K load tests. Therefore, the P_{90} load tests for pairs 4 and 6 were eliminated. The variable P_{90} load tests on the stronger pairs appear to produce so much wear that the rider specimens would be worn down to the arm in a very short time. Therefore, load P_{75} , equal to the load required to achieve 75% of the 0.2% CYS or UTS of the weakest material of each pair, was chosen as the variable load for pairs 3, 5 and 7. Pair 7 would have only one level of loading, since the P_{75} level of loading is the same as the H load.

The equations used to calculate the Hertzian stresses and the loads to be applied on the specimens are given below; the basic equation (7) used is for compression between a sphere and a flat plate:



$$\text{Max } s_c = 0.918 \sqrt[3]{\frac{P}{D^2 \left[\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \right]^2}} \quad (\text{Eq. 1})$$

where:

ν = Poisson's ratio

D = sphere diameter, inch

E = modulus of elasticity, psi

P = compressive load, lb

s_c = unit compressive stress, psi

Subscripts 1 and 2 refer to bodies 1 and 2

For the nominal spherical diameter of 0.2495 inch:

$$\text{Max } s_c = 2.3163 \sqrt[3]{\frac{P}{\left[\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \right]^2}}$$

or:

$$P = 0.0805 (\text{Max } s_c)^3 \left[\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \right]^2 \quad (\text{Eq. 2})$$

For a nominal spherical diameter of 0.2495 inch and $\text{Max } s_c = 90\%$ (0.2% CYS)⁽¹⁾ or 90% (UCS)⁽²⁾:

$$P_{90} = 0.0585 (0.2\% \text{ CYS})^3 \left[\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \right]^2 \quad (\text{Eq. 3})$$

For a nominal spherical diameter of 0.2495 inch and $\text{Max } s_c = 75\%$ (0.2% CYS) or 75% (UCS):

$$P_{75} = 0.0339 (0.2\% \text{ CYS})^3 \left[\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \right]^2 \quad (\text{Eq. 4})$$

or:

$$P_{75} = 0.5787 P_{90} \quad (\text{Eq. 4b})$$

(1) CYS = compressive yield strength

(2) UCS = ultimate compressive strength

For a nominal spherical diameter of 0.2495 inch and Max $s_c = 25\%$ (0.2% CYS) or 25% (UCS):

$$P_{25} = 0.0013 (0.2\% \text{ CYS})^3 \left[\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \right]^2 \quad (\text{Eq. 5a})$$

or:

$$P_{25} = 0.0214 P_{90} \quad (\text{Eq. 5b})$$

For a nominal spherical diameter of 0.2495 inch and a material loaded against itself (pairs 3, 5 and 7):

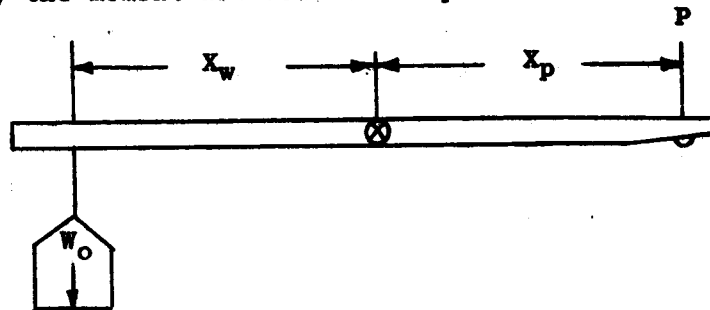
$$P_{90s} = 0.2346 (0.2\% \text{ CYS})^3 \left[\frac{1-\nu}{E} \right]^2 \quad (\text{Eq. 6})$$

$$P_{75s} = 0.5787 P_{90s} = 0.1358 (0.2\% \text{ CYS})^3 \left[\frac{1-\nu}{E} \right]^2 \quad (\text{Eq. 7})$$

$$P_{25s} = 0.0214 P_{90s} = 0.0050 (0.2\% \text{ CYS})^3 \left[\frac{1-\nu}{E} \right]^2 \quad (\text{Eq. 8})$$

The compressive loads P between specimens will be calculated for each temperature by using the 0.2% CYS or UCS, ν and E of the materials at that temperature.

The weight in the load try (above the tare weight) is related to the above compressive loads by the moment arm relationships:



$$W_o = \left(\frac{x_p}{x_w} \right) P$$

$$W_o = \frac{4.880}{5.625} P = 0.868P. \quad (\text{Eq. 9})$$

Since the line of action of the connector between the force pickup and the arm is at the same distance from the gimbal as the line of action of the load W_0 , the same moment-arm relationship exists between the force pickup force, F_{fp} , and the frictional force, F_f , between the specimens:

$$F_{fp} = \left(\frac{x_p}{x_w} \right) F_f = 0.868 F_f.$$

If the coefficient of friction $f = 1$:

$$F_f = fP = P$$

$$1 F_{fp} = 0.868P = W_0 \quad \text{For: } \begin{bmatrix} x_{fp} = x_w \\ f = 1 \end{bmatrix} \quad (\text{Eq. 10})$$

The calculations of loads P and weights W for all test conditions where material properties are known are given in Table XIV and plotted in Figure 34.

Specimen Testing

The high vacuum friction and wear tester was assembled and the first series of tests were completed. Prior to assembly, the test specimens were cleaned and pretest data obtained in the following sequence:

- Visual examination for surface defects
- Clean
 - Degrease - acetone
 - Rinse - distilled water
- Penetrant inspection
- Rinse - hot tap water/distilled water
- Surface finish measurements
 - Riders - 100%, Tallysurf
 - Discs - 100% profilometer
 - Each material, Tallysurf
- Clean - ultrasonic
- Weight measurements

Four sets of rider and disc specimens are assembled in the tester at one time so that the four sets of specimens will have the same bakeout history and heating history when the tests are run at elevated temperature. Therefore, the test data will be presented in groups of test assemblies. During the report interim, eleven tests were conducted with the test conditions and results being summarized in Table XV. In addition to the Sanborn traces, the format used to record the test

data is shown in Appendix II. The Sanborn traces showing the change in friction coefficients with time, photographs of the test specimens illustrating the wear patterns, pretest and post-test weight data and surface finish measurements will be presented after analysis of the data has been completed. Although a detailed analysis of the tests results is in progress and will be discussed in subsequent progress reports, a preliminary evaluation indicates that the data to be obtained at very low loads can be improved by making two modifications to the test facility:

1. Replacement of the 20-pound force pickups with 2-pound force pickups will result in more accurate data for the lightly loaded specimens, inasmuch as errors in calibration, hysteresis, signal zeroing and reading will constitute a smaller fraction of the signal.
2. Reduction of the spring constant of the loading arm bellows will result in more constant loading of specimens which exhibit considerable wear under very light loads. At present, the spring can substantially reduce the load after a few thousandths of an inch wear when the applied load is on the order of 0.1 pound. This is not a problem prior to significant wear or when the load is on the order of a few pounds; however, an improved bellows arrangement will be advantageous for use with those material combinations which exhibit significant wear at low loads.

It is planned to modify the test facility during the next quarter to incorporate the above indicated improvements.

VI. FUTURE PLANS

The summary which follows enumerates the steps to be pursued during the succeeding quarter to implement this study.

1. Evaluation of the corrosion specimens which were exposed to potassium for 1000 hours at 800° and 1200°F will continue.
2. The 1000-hour isothermal corrosion tests of selected pairs of candidate bearing materials contained in Cb-1Zr alloy capsules will be completed at 800°, 1200° and 1600°F.
3. The compression load train and tantalum strip heater will be installed in the vacuum chamber and checkout tests for the elevated temperature compression tests will be completed.
4. Checkout tests of the potassium wetting facility will be completed.
5. Modification of the loading arm bellows arrangement of the friction and wear testers will be completed and friction testing in high vacuum will be continued.

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APPENDICES

APPENDIX I

TEST SPECIMEN CONTROL SHEET

APPENDIX I

TEST SPECIMEN CONTROL SHEET

TEST NO.		TEST TITLE		SPECIMEN MATERIAL		COMPANION SPECIMEN	TEST DATE
				SPECIMEN MCH		COMPANION MCH	CONTRACT NO.
				RIDER			
				DISC			

PRE-TEST DATA		REMARKS
A	VISUAL EXAMINATION	
CLEAN:		
B	(1) DEGREASE - ACETONE	
	(2) RINSE - TAP WATER	
	(3) RINSE - DISTILLED WATER	
C	PENETRANT INSPECTION	
CLEAN:		
D	(1) RINSE - HOT TAP WATER	
	(2) RINSE - DISTILLED WATER	
SURFACE FINISH (RMS):		
E	(1)	
	(2)	
	(3)	
	(4)	
	(5)	
	(6)	
F	CLEAN - ULTRASONIC	
WEIGHT, GM (Avg. of 3 readings):		
G	(1)	
	(2)	
	(3)	
	AVERAGE VALUE	

POST-TEST DATA		REMARKS
A	VISUAL EXAMINATION	
WEIGHT, GM (Avg. of 3 readings):		
B	(1)	
	(2)	
	(3)	
	AVERAGE VALUE	
C	PHOTOGRAPH	
D	CLEAN - ULTRASONIC	
WEIGHT, GM (Avg. of 3 readings):		
E	(1)	
	(2)	
	(3)	
	AVERAGE VALUE	
F	WEIGHT CHANGE, GMS	
G	MATERIAL DENSITY, G/CM ³	
H	VOLUME CHANGE, CM ³	
I	DIAMETER OF WEAR SCAR	
J	WIDTH OF WEAR SCAR	
SURFACE FINISH (RMS):		
K	(1)	
	(2)	
	(3)	
	(4)	
	(5)	
	(6)	

10 1131

APPENDIX II

DATA SHEET FOR FRICTION AND WEAR TESTS

Disc Material: 1 _____
2 _____
3 _____
4 _____

[illegible]

35-1

APPENDIX II

Rider Material: 1

Personnel :

2

3

4

[illegible]

35-2

TABLE I. CANDIDATE BEARING MATERIALS

<u>Material Class</u>	<u>Candidate Material</u>	<u>Nominal Composition</u>
A. Nonrefractory Metals and Alloys	Star J	17%W-32%Cr-2.5%Ni-3%Fe-2.5%C-Bal. Co
B. Refractory Metals and Alloys	Mo-TZM (Arc Cast; Stress-Relieved)	0.5%Ti-0.08%Zr-0.02%C-Bal. Mo
	Tungsten (Arc Cast; Stress-Relieved)	99.96%W (Min.)
C. Fe-Ni-Co Bonded Carbides	Carboloy 907	74%WC-20%TaC-6%Co
	Carboloy 999	97%WC-3%Co
	K601	84.5%W-10%Ta-5.5%C
D. Refractory Compounds - Oxides, Carbides, Borides	Lucalox	99.8%Al ₂ O ₃ (Min.)-0.1%MgO-0.02%SiO ₂ -0.02%CaO-0.02%Fe ₂ O ₃
	Zircoa 1027	95.5%ZrO ₂ -Bal. Proprietary
	Titanium Carbide	94%TiC-4.25%WC-0.9%Ni-0.1%Fe-0.68%Co
	Titanium Diboride	98%TiB ₂ -0.39%Fe-0.30%C
E. Refractory Metal Bonded Carbided	TiC+5%W	90%TiC-4.79%WC-5%W-0.36%Fe
	TiC+10%Mo	85.4%TiC-10.5%Mo-3.99%WC-0.13%Fe
	TiC+10%Cb	83.6%TiC-9.54%Cb-5.85%WC-0.73%Co-0.33%Fe
	Grade 7178	85.6%W-6.9%Mo-1.8%Cb-0.3%Ti-5.7%C

TABLE II. PROCUREMENT STATUS OF CANDIDATE BEARING MATERIALS TEST SPECIMENS

Material	Spec.	Vendors	Test Specimens Identity							MCN Series
			Corrosion		Disc		Rider			
			Qty.	Promise/ Delivery Date	Qty.	Promise/ Delivery Date	Qty.	Promise/ Delivery Date		
Mo-TZM (Raw Stock)	SPPS-15	American Metal Climax	0.437" ϕ x 36"	3-23-65	10-each 0.187" thk. x 4.375" x 4.375"	3-25-65	0.250" ϕ x 36"	3-23-65	1084 1085 1086	
Mo-TZM (Machining)	---	Dawson Carbide	15	4-10-65	10	5-3-65	74	5-18-65	1037	
Carboloy 907	SPPS-23T	GE--MPD	--(1)	--	17(2)	5-3-65	18	5-3-65	1036	
Grade 7178	SPPS-36T	Kennametal, Inc.	--(1)	--	11 25	7-27-65 --	56(3)	7-15-65 --(6)	1046	
TiC+10%Cb	SPPS-35T	Kennametal, Inc.	--(1)		11(4) 16 8	7-27-65 8-25-65 --(6)	26(5) 5	6-30-65 --(6)	1046	

(1) Corrosion Test Specimens are on Hand at General Electric.

(2) Two Specimens Rejected for Surface Defects.

(3) Two Specimens Rejected for Surface Defects.

(4) Two Specimens Rejected for Surface Defects.

(5) Four Specimens Rejected for Surface Defects.

(6) Delivery Uncertain Due to Strike at Vendor's Plant.

**TABLE III. INSPECTION RESULTS OF Cb-1Zr ALLOY SHEATHED
BN INSULATED IMMERSION HEATERS**

<u>Heater Identification</u>	<u>Penetrant (PEP) Inspection</u>	<u>Radiographic Inspection</u>	<u>Resistance Across BN Insulation at 500 Volt Potential Megohm</u>
J3NX12A-1 ⁽¹⁾	No indications	Heater winding uni- formly spaced	11,000
J3NX12A-2 ⁽¹⁾	No indications	Heater winding uni- formly spaced	4,200
J3NX12A-3	No indications	Heater windings close to sheath at top	4,000
J3NX12A-4	No indications	Heater windings close to sheath at top	5,000
J3NX12A-5	No indications	Heater windings close to sheath at top	9,500
J3NX12A-6 ⁽¹⁾	No indications	Heater windings uni- formly spaced	7,200
J3NX12A-7 ⁽¹⁾	No indications	Heater windings uni- formly spaced	13,000
J3NX12A-8	No indications	Heater windings uni- formly spaced	5,000
J3NX12A-9	No indications	Heater windings bent and close to sheath at top	3,000
J3NX12A-10 ⁽¹⁾	No indications	Heater winding uni- formly spaced	1,400
J3NX12A-11	No indications	Heater windings bent and close to sheath at top--foreign object 2/3 from top; rejected	2,200
J3NX12A-12 ⁽¹⁾	No indications	Heater winding uni- formly spaced	8,700
J3NX12A-13	No indications	Heater windings slightly bent at top	3,500
J3NX12A-14 ⁽¹⁾	No indications	Heater winding uni- formly spaced	750

(1) Selected for Heater Assembly.

TABLE IV. CHEMICAL ANALYSES⁽¹⁾ OF POTASSIUM USED FOR
THIRD 1,000-HOUR ISOTHERMAL CAPSULE CORROSION TESTS

<u>Sample Identity</u>	<u>Sample Location</u>	<u>Sample Weight, Grms.</u>	<u>Oxygen⁽²⁾ Content, ppm</u>
Capsule Nos. 55,61,62	From Transfer Line	3.844(3)	3.2
		1.978(3)	<u>7.1</u>
			Avg. 5.15(4)
Capsule Nos. 55,61,62	Cast Inside EB Tank	3.844(3)	4.7
		1.908(3)	<u>5.4</u>
			Avg. 5.05(4)
Capsule Nos. 56,57,58, 59,60	From Transfer Line	4.806(3)	4.4
		1.908(3)	<u>9.1</u>
			Avg. 6.75(4)
Capsule Nos. 56,57,58, 59,60	Cast Inside EB Tank	3.933(3)	4.1
		1.900(3)	<u>9.1</u>
			Avg. 6.6(4)
Capsule Nos. 51,52,53, 54	Cast Inside EB Tank	3.777(3)	10.1
		1.877(3)	<u>11.8</u>
			Avg. 10.95(4)

(1) By Mercury Amalgamation Method.

(2) As K₂O.

(3) Helium Cover Gas Used During Analyses.

(4) Average Calculated by Total u Grams Oxygen/Total Weight
with No Blank Being Subtracted.

TABLE V. CHEMICAL ANALYSES OF METALLIC IMPURITIES IN POTASSIUM
USED FOR THE THIRD 1,000-HOUR ISOTHERMAL CAPSULE CORROSION TEST

Capsule No.	Lab No.	Chemical Analyses (1,2), ppm															
		Ag	Al	B	Be	Ca	Cb	Co	Cr	Cu	Fe	Mg	Mn	Mo	Na	Ni	Pb
51, 52, 53, 54	193	<1	<1	<1	<25	5	<1	<1	<1	<1	1	<1	<1	<1	15	<1	<1
55, 61, 62	196	<1	1	<1	<25	1	<1	<1	<1	<1	<1	<1	<1	<1	5	<1	<1

- (1) Metallic Impurities in KCl Analyzed by Spectrographic Techniques.
(2) Sampler Cast Inside EB Tank Under Vacuum at Same Time Indicated Capsules were Filled.

TABLE VI. TEST TEMPERATURE FOR THIRD 1000-HOUR
ISOTHERMAL CAPSULE CORROSION TEST

Susceptor Number	Capsule Numbers	Test Temp., °F	Mean Temp.	
			°F	%
1	49, 51, 55, 56, 59	800	797	±11.9 ±1.48
2	52, 54, 57, 60, 62	1200	1197	±15.2 ±1.26
3	53, 56, 61	1600	1595	± 8.5 ±0.53

TABLE VII. DIMENSIONAL AND WEIGHT CHANGES OF SPECIMENS EXPOSED IN POTASSIUM FOR 1000 HOURS AT 1200°F

Specimen Identity MCM No.	Specimen Length, inches Before Test	Specimen Width, inches Before Test	Dimensional Change Percent	Dimensional Change Inches x 10 ⁻³	Specimen Length, inches After Test	Specimen Width, inches After Test	Dimensional Change Percent	Dimensional Change Inches x 10 ⁻³	Specimen Weight in Grams Before Test	Specimen Weight in Grams After Test	Weight Change Milligrams Mg/Cu
T12a	2.00386	0.24671	+0.03	+0.16	2.00389	0.24687	+0.077	+0.08	8.7813	8.7822	+1.0
Capsule #	2.00003	0.24656	+0.15	+0.19	2.00018	0.24675	+0.036	+0.02	8.7646	8.7655	+0.9
T1C-43	2.00139	0.25163	+0.31	+0.09	2.00150	0.25171	+0.018	+0.02	11.2329	11.2330	+0.1
Capsule #	2.00134	0.25136	+0.10	+0.04	2.00144	0.25210	+0.008	+0.008	11.2390	11.2391	+0.1

TABLE VIII. DIMENSIONAL AND WEIGHT CHANGES OF SPECIMENS EXPOSED IN POTASSIUM FOR 1000 HOURS AT 800°F

Specimen Identity Material	Specimen Location	Specimen Length, Inches			Specimen Width, Inches			Specimen Thickness, Inches			Specimen Weight, Grams			Weight Change Milligrams
		Test	Before	After	Test	Before	After	Test	Before	After	Test	Before	After	
Carboloy 999	Liquid	2.00338	2.00393	+0.40	+0.050	0.25147	0.25132	+0.08	+0.020	0.25128	0.25179	+0.50	+0.199	0.0
Capsule BIC-11	Vapor	2.00387	2.00313	+0.46	+0.023	0.25158	0.25199	+0.04	+0.016	0.25161	0.25181	0.00	0.000	0.0
Carboloy 807	Liquid	2.00361	2.00306	+0.45	+0.023	0.25132	0.25199	+0.07	+0.028	0.25175	0.25181	+0.06	+0.024	+0.7
Capsule BIC-35	Vapor	2.00379	2.00377	+0.48	+0.024	0.25028	0.25041	-0.05	-0.013	0.25126	0.25129	+0.04	+0.016	+0.081
Mo-72M(1)	Liquid	2.00006	2.00003	-0.03	-0.003	0.24782	0.24784	-0.08	-0.023	0.24817	0.24811	-0.06	-0.024	-0.4
Capsule BIC-13	Vapor	2.00043	2.00073	+0.30	+0.010	0.24793	0.24786	-0.07	-0.028	0.24821	0.24810	-0.11	-0.044	0.0
Unalloyed	Liquid	2.00118	2.00106	-0.12	-0.006	0.25030	0.25007	-0.13	-0.023	0.25057	0.25060	-0.07	-0.028	0.0
Tungsten (S)	Vapor	2.00112	2.00129	+0.17	+0.008	0.25045	0.25060	-0.08	-0.020	0.25020	0.25014	-0.06	-0.024	-0.5
Lucalox (Al ₂ O ₃)	Liquid	2.00264	2.00266	-0.16	-0.006	0.25069	0.25068	-0.01	-0.004	0.25004	0.25003	-0.01	-0.004	+0.1
Capsule BIC-21	Vapor	2.00326	2.00337	-0.01	-0.001	0.25012	0.25012	0.00	0.000	0.25016	0.25016	0.00	0.000	-0.3
Sirom 1027	Liquid	1.99979	1.99973	+0.04	+0.047	0.25040	0.25070	+0.30	+0.199	0.25105	0.25129	+0.24	+0.066	+0.3
Capsule BIC-22	Vapor	1.99948	1.99943	+1.17	+0.048	0.25010	0.25026	+0.16	+0.064	0.25196	0.25226	+0.29	+0.115	-0.1
W801	Liquid	2.00162	2.00167	+0.05	+0.002	0.25188	0.25214	+0.19	+0.075	0.25256	0.25279	+0.20	+0.079	-0.3
Capsule BIC-41	Vapor	2.00162	2.00175	+0.13	+0.006	0.25254	0.25278	+0.23	+0.087	0.25187	0.25244	+0.57	+0.326	+0.5
TiC	Liquid	2.00069	2.00060	-0.09	-0.004	0.25132	0.25159	+0.07	+0.028	0.25202	0.25242	+0.10	+0.040	+0.3
Capsule BIC-35	Vapor	2.00046	2.00046	-0.01	-0.001	0.25221	0.25240	+0.09	+0.036	0.25222	0.25242	+0.08	+0.020	-1.7
TiC-92W	Liquid	2.00230	2.00223	-0.06	-0.004	0.25205	0.25209	+0.04	+0.016	0.25176	0.25181	+0.05	+0.028	-1.1
Capsule BIC-44	Vapor	2.00210	2.00181	-0.29	-0.014	0.25171	0.25176	+0.05	+0.020	0.25206	0.25215	+0.07	+0.064	-0.3
TiC-102W	Liquid	2.00141	2.00144	+0.03	+0.002	0.25163	0.25171	+0.08	+0.020	0.25162	0.25176	+0.16	+0.064	-0.3
Capsule BIC-49	Vapor	2.00134	2.00146	+0.23	+0.011	0.25218	0.25219	0.00	0.000	0.25209	0.25209	0.00	0.000	-0.2
TiC-102W	Liquid	2.00052	2.00044	-0.08	-0.004	0.25240	0.25245	+0.05	+0.020	0.25202	0.25206	+0.03	+0.012	-0.8
Capsule BIC-29	Vapor	2.00031	2.00032	+0.01	+0.001	0.25223	0.25228	+0.05	+0.020	0.25240	0.25249	+0.09	+0.026	-1.0
Grade 7178	Liquid	2.00289	2.00274	+0.06	+0.002	0.25113	0.25164	+0.51	+0.303	0.25122	0.25123	-0.19	-0.076	-1.1
Capsule BIC-32	Vapor	2.00208	2.00254	+0.46	+0.023	0.25142	0.25130	-0.12	-0.048	0.25129	0.25176	+0.47	+0.187	-0.060
Star J(2)	Liquid	2.00108	2.00087	-0.21	-0.010	0.25206	0.25225	+0.16	+0.047	0.25224	0.25241	+0.17	+0.067	-0.313
Capsule BIC-38	Vapor	2.00125	2.00099	-0.26	-0.026	0.25219	0.25223	+0.18	+0.071	0.25212	0.25226	+0.22	+0.067	-0.022
TiB2	Liquid	2.00431	2.00433	+0.01	+0.001	0.25197	0.25206	+0.09	+0.025	0.24690	0.24709	+0.19	+0.077	+0.109
Capsule BIC-31	Vapor	2.00126	2.00129	+0.31	+0.006	0.25306	0.25314	+0.08	+0.023	0.24674	0.24699	+0.19	+0.061	+0.067

(1) Stress-Relieved for 1/2 Hour at 2200°F.

(2) Stress-Relieved for 1 Hour at 2200°F.

(3) As-Cast.

TABLE IX. SUMMARY OF DIMENSIONAL AND WEIGHT CHANGES OF SPECIMENS EXPOSED IN POTASSIUM FOR 1000 HOURS

Material	Specimen Location	Dimensional Changes (1), Inches x 10 ³						Weight Change (2), mg/cm ²			
		Specimens Exposed at 1600°F (3)			Specimens Exposed at 1200°F (4)			Specimens Exposed at 1600°F (3)		Specimens Exposed at 1200°F (4)	
		Length	Width	Width ₂	Length	Width	Width ₂	Length	Width	Length	Width
Carboloy 999	Liquid	-0.10	-0.26	-0.38	+0.28	+0.12	+0.01	+0.40	+0.05	-0.793	+0.05
	Vapor	-0.27	-0.06	-0.10	+0.30	+0.03	+0.05	+0.46	+0.04	-0.283	0.000
Carboloy 907	Liquid	+0.69	+0.73	+0.57	+0.58	+0.04	+0.03	+0.45	+0.07	-0.218	+0.06
	Vapor	-0.22	-0.01	-0.02	+0.69	+0.05	+0.04	+0.48	+0.03	0.000	+0.04
Mo-TZM (6)	Liquid	-0.06	-0.19	-0.20	-0.13	-0.16	-0.02	-0.03	-0.08	-0.050	-0.06
	Vapor	-0.04	-0.19	-0.20	-0.10	-0.09	0.00	+0.20	-0.07	-0.036	-0.11
Unalloyed Tungsten (7)	Liquid	-0.02	-0.11	-0.09	+0.04	+0.15	-0.04	-0.12	-0.13	-0.007	-0.07
	Vapor	+0.08	-0.05	0.00	-0.34	+0.02	+0.03	+0.17	-0.05	-0.029	-0.06
Lucalox (Al ₂ O ₃)	Liquid	-2.44	+0.46	+0.39	+0.05	+0.04	+0.05	-0.16	-0.01	+0.353	-0.01
	Vapor	+0.83	+0.80	+0.62	+0.03	+0.01	0.00	-0.01	0.00	+0.465	0.00
Zircaloy 1027 (ZrO ₂)	Liquid	+13.99	+1.74	+2.01	+0.63	+0.08	+0.09	+0.94	+0.30	+1.157	+0.24
	Vapor	+15.54	+2.20	+2.27	+0.99	+0.24	+0.50	+1.17	+0.16	+1.696	+0.29
K-801	Liquid	+0.03	+0.18	+0.11	+0.11	+0.22	+0.24	+0.05	+0.19	-0.829	+0.20
	Vapor	+0.02	+0.18	+0.21	+0.08	+0.23	+0.21	+0.13	+0.22	-0.101	+0.57
TiC	Liquid	+0.06	+0.01	+0.09	-0.04	-0.02	-0.02	-0.09	+0.07	-0.050	+0.04
	Vapor	-0.14	+0.01	0.00	+0.10	+0.03	+0.02	-0.01	+0.09	-0.036	+0.10
TiC+5%W	Liquid	+0.15	+0.04	+0.06	+0.17	+0.06	+0.16	-0.08	+0.04	+0.014	+0.05
	Vapor	+0.06	+0.04	+0.04	+0.13	+0.07	+0.17	-0.29	+0.05	-0.116	+0.07
TiC+10%Mo	Liquid	-0.02	+0.04	+0.04	+0.21	+0.09	+0.02	+0.03	+0.08	-0.072	+0.16
	Vapor	+0.04	+0.05	+0.06	+0.10	+0.04	+0.02	+0.22	0.00	-0.094	0.00
TiC+10%Cb	Liquid	-0.03	+0.03	+0.03	0.00	+0.03	+0.01	-0.08	+0.05	-0.043	+0.03
	Vapor	+0.03	+0.03	+0.03	-0.02	-0.03	-0.02	+0.01	+0.05	-0.101	+0.09
Grade 7178	Liquid	-0.12	+0.16	+0.16	+0.01	+0.15	+0.20	+0.05	+0.51	-0.344	-0.19
	Vapor	-0.21	+0.18	+0.16	+0.20	+0.21	+0.20	+0.40	+0.12	-0.101	+0.47
Star J (8)	Liquid	+0.65	+0.11	+0.63	-0.75	+0.14	+0.16	-0.21	+0.17	-0.669	+0.17
	Vapor	+0.97	+0.32	+0.37	-0.14	+0.18	+0.16	-0.53	+0.18	-0.167	+0.22
TiB ₂	Liquid	+0.10	-0.02	-0.02	+0.03	+0.16	+0.08	+0.01	+0.09	+0.109	+0.19
	Vapor	-0.03	-0.07	-0.04	+0.15	+0.19	---	+0.11	+0.08	-0.050	+0.15

(5) Complete Data Found on Page 43 of this Report.

(6) Stress-Relieved 1/2 Hour at 2250°F.

(7) Stress-Relieved 1 Hour at 2000°F.

(8) As-Cast.

(1) Specimen Dimensions: 2.00 Inches x 0.25 Inch x 0.25 Inch.

(2) Calculated by Dividing Actual Weight Loss by Specimen Surface Area (13.738 cm²).

(3) Complete Data Found in Quarterly Progress Report No. 7.

(4) Complete Data Found in Quarterly Progress Report No. 8.

TABLE X. VISUAL EXAMINATION OF CORROSION TEST SPECIMENS AFTER
A 1600-HOUR EXPOSURE TO POTASSIUM AT 1200°F

Capsule No.	Specimen Identity		Specimen Location	Description
	Material	MCN No.		
BIC-15	Mo-TZM	1037-A5	Liquid	The surface of the specimen has a bright and shiny appearance. A discoloration was observed where the Cb-lZr alloy wire cage touched the specimen. Scratches were visible on the surface and one longitudinal edge was rounded.
BIC-15	Mo-TZM	1037-A6	Vapor	The specimen looks the same as the liquid region specimen except for the absence of marks where the Cb-lZr alloy wire cage touched the specimen.
BIC-30	TiC+10%Cb	1045-A3	Liquid	The surface of the specimen is dull grey in color. No reaction was observed between the Cb-lZr alloy wire cage and the specimen. The longitudinal edges showed some chipping. Small holes were observed in several places on the surface and a small particle is lodged on one surface.
BIC-30	TiC+10%Cb	1045-A4	Vapor	The specimen looks the same as the liquid region specimen except a discoloration was noted where the Cb-lZr alloy wire cage was in contact with the specimen.
BIC-33	Grade 7178	1046-A3	Liquid	The surface of the specimen is dull grey in color. Some chipping of the edges is evident. Discolorations were observed where the Cb-lZr alloy wire cage touched the specimen.
BIC-33	Grade 7178	1046-A4	Vapor	The specimen looks the same as the liquid region specimen except there is no chipping of the edges and there are transverse scratches on one side of the specimen.
BIC-36	TiC	1042-A3	Liquid	The surface of the specimen is dull grey in color. Some chipping of the edges was observed. There was no reaction between the Cb-lZr alloy cage and the specimen.

TABLE X. (Cont'd)

Capsule No.	Specimen Identity		Specimen Location	Description
	Material	MCN No.		
BIC-36	TiC	1042-A4	Vapor	The specimen looks the same as the liquid region specimen.
BIC-39	Star J	1047-A3	Liquid	The surface of the specimen has a bright shiny appearance. Discolorations can be observed where the Cb-lZr alloy wire cage touched the specimen. Crazed pattern is observed on the surface of the specimen.
BIC-39	Star J	1047-A4	Vapor	The specimen looks the same as the liquid region specimen except for the presence of a small hole on the surface.
BIC-42	K601	1041-A3	Liquid	The surface of the specimen has a shiny appearance with occasional brown spots and pits present on the surface.
BIC-42	K601	1041-A4	Vapor	The specimen looks the same as the liquid region specimen.

TABLE XI. VISUAL EXAMINATION OF CORROSION TEST SPECIMENS AFTER
A 1000-HOUR EXPOSURE TO POTASSIUM AT 800°F

Capsule No.	Specimen Identity		Specimen Location	Description
	Material	MCN No.		
BIC-22	Zircoa 1027	1040-A1	Liquid	The entire out surface of the specimen changed to a dark tan after testing. However, when sectioned, the dark tan layer was found to be approximately 0.025-inch deep around the periphery of the specimen. The core of the specimen remained yellow in color, which is the pre-test color. Black specks are evident on the surface with a shiny black substance in occasional pits.
BIC-22	Zircoa 1027	1040-A2	Vapor	The specimen is identical in appearance to the liquid region specimen.
BIC-13	Mo-TZM	1037-A1	Liquid	The surface has a dull silvery appearance with brown spots and a blue tint in some areas. Discoloration was observed where the Cb-Izr alloy wire cage came in contact with the specimen.
BIC-13	Mo-TZM	1037-A2	Vapor	The surface appearance is identical to that of the liquid region specimen except for the presence of small pits surrounded by black rings.
BIC-18	Unalloyed Tungsten	1038-A5	Liquid	The surface is dull grey in color with darker areas having a swirl pattern. Discolorations are evident where the Cb-Izr alloy wire cage came in contact with the specimen.
BIC-18	Unalloyed Tungsten	1038-A6	Vapor	The specimen has the same appearance as the liquid region specimen except for the presence of small pits and a rough surface texture.
BIC-32	Grade 7178	1046-A1	Liquid	The specimen has a dull grey appearance with no apparent marks from the Cb-Izr alloy wire cage.

TABLE XI. (Cont'd)

<u>Capsule No.</u>	<u>Material</u>	<u>MCN No.</u>	<u>Specimen Location</u>	<u>Description</u>
BIC-32	Grade 7178	1046-A2	Vapor	The surface is a dark grey to black in color with a definite swirl pattern. The edges show some chipping and discolorations are present where the Cb-lZr alloy wire cage touched the specimen.
BIC-41	K601	1041-A1	Liquid	The surface has a dull silvery appearance with a distinct flow pattern on one end. The surface is pitted and the edges are chipped. Discolorations are evident where the Cb-lZr alloy wire cage was in contact with the specimen.
BIC-41	K601	1041-A2	Vapor	The specimen looks identical to the liquid region specimen except for a pigskin pattern on the surface. No edge chips were observed.

TABLE XII. HIGH VACUUM FRICTION AND WEAR TEST-PLAN SCHEDULE

Temp. °F	PAIR	500 SFM		5000 SFM	
		K/H Load	P ₇₅ Load	K/H Load	P ₇₅ Load
RT (22 Tests)	1	100K05A 100K05B		100K50A	
	2	200K05A 200K05B		200K50A	
	3	300H05A	300705A	300H50A	
	4		400905A 400705A	400K50A	
	5	500K05A	500905A 500705A 500705B	500H50A	
	6	600K05A 600K05B		600K50A	
	7	700H05A		700H50A	
400°F (20 Tests)	1	104K05A		104K50A 104K50B	
	2	204K05A		204K50A 204K50B	
	3	304H05A		304H50A	304750A
	4		404905A	404K50A 404K50B	
	5	504K05A		504H50A	504750A
	6	604K05A		604K50A 604K50B	
	7	704H05A		704H50A	
800°F (20 Tests)	1	108K05A		108K50A 108K50B	
	2	208K05A		208K50A 208K50B	
	3		308705A	308H50A	308750A
	4	408K05A		408K50A 408K50B	
	5		508705A	508H50A	508750A
	6	608K05A		608K50A 608K50B	
	7	708H05A		708H50A	

Code:

7 16 K 05 A

First test or repeat
Speed in 100's of RPM
Load*
- Temperature in 100's of °F
- Materials Pair

* K = Constant load (Pairs 1, 2, 4, 6)
H = Constant load (Pairs 3, 5, 7)
7 = 75% UCS or 75% 0.2% CYS
9 = 90% UCS or 90% 0.2% CYS

Temp. °F	PAIR	500 SFM		5000 SFM	
		K/H Load	P ₇₅ Load	K/H Load	P ₇₅ Load
1200°F (24 Tests)	1	112K05A 112K05B		112K50A 112K50B	
	2	212K05A 212K05B		212K50A 212K50B	
	3	312H05A	312705A	312H50A	
	4	412K05A 412K05B		412K50A 412K50B	
	5	512H05A	512705A	512H50A	
	6	612K05A 612K05B		612K50A 612K50B	
	7	712H05A		712H50A	
1600°F (20 Tests)	1	116K05A 116K05B		116K50A	
	2	216K05A 216K05B		216K50A	
	3	316H05A	316705A		316750A
	4	416K05A 416K05B		416K50A	
	5	516H05A	516705A		516750A
	6	616K05A 616K05B		616K50A	
	7	716H05A		716750A	

TABLE XIII. TEST SPECIMEN PAIR IDENTIFICATION

Material	Pair						
	1	2	3	4	5	6	7
Carboloy				■	● ■		
Grade 7178	■	●	● ■				
TiC+10%Cb						■	● ■
Mo-TZM	●	■		●		●	

● = Hemispherical Rider Specimen.

■ = Disc Specimen.

TABLE XIV. CALCULATED LOADS P_{90} , P_{75} , P_{25} , TO PRODUCE STRESSES BETWEEN FRICTION AND WEAR SPECIMENS EQUAL TO 90%, 75% AND 25% OF THE 0.2% CYS OR UCS

PAIR	MATERIAL	POISS. RATIO ν	TEMP. $^{\circ}\text{F}$	E $\text{psi} \times 10^6$	$\frac{1 - \nu_1}{E_1}$ $\text{psi} \times 10^8$	$\frac{1 - \nu_2}{E_2}$ $\text{psi} \times 10^8$	$\frac{1 - \nu_2}{E}$ $\text{psi} \times 10^8$	$\left[\frac{1 - \nu_2}{E} \right]^2$ $\text{psi} \times 10^{16}$	(a) $\frac{1 - \nu_2}{E}$ $\text{psi} \times 10^8$ or UCS or (UCS) ³ $\text{psi} \times 10^{-15}$	(b) P_{90} Pounds	(c) P_{90} Pounds	(d) P_{75} Pounds	(e) P_{75} Pounds	(c) P_{25} Pounds	(e) P_{25} Pounds
1	TZM [7178] [7178] [7178] [TZM]		RT 400 800 1200 1600		2.1187 2.2518 2.4373 2.6561 2.9181	1.1335 1.1455 1.1590 1.1800 1.2046	3.2522 3.3973 3.5863 3.8361 4.1044	10.577 11.542 12.662 14.716 17.246	1.304 1.183 1.021 0.819 0.561	0.0809 0.0801 0.0668 0.0770 0.0701	0.0701 0.0668 0.0613 0.0561 0.0516	0.0468 0.0463 0.0463 0.0463 0.0463	0.0406 0.0402 0.0402 0.0402 0.0402	0.0264 0.0264 0.0264 0.0264 0.0264	0.025 0.025 0.025 0.025 0.025
2															
3	7178 [7178] [7178] [TZM]	0.22	RT 400 800 1200 1600	83.95 83.08 82.11 80.65 -	1.1335 1.1455 1.1590 1.1800 -	1.1335 1.1455 1.1590 1.1800 -	2.2670 2.2910 2.3180 2.3600 -	5.1393 5.2487 5.3731 5.5686 -	350.40 321.77 234.98 120.71 15.625	10.564 9.907 7.346 3.944 -	9.1645 8.5949 6.4354 3.4213 -	6.1134 5.7331 4.2860 2.2822 -	5.3038 4.9739 3.7184 1.9800 -	0.2264 0.2193 0.1377 0.0945 -	0.1964 0.1842 0.1377 0.0783 -
4	TZM [C907] [C907] [C907]		RT 400 800 1200 1600		2.1187 2.2518 2.4373 2.6561 2.9181	1.2046 1.2172 1.2317 1.2539 -	3.3233 3.4690 3.6690 3.9100 -	11.044 12.034 13.462 15.286 -	1.304 1.183 1.021 0.819 0.561	0.0845 0.0724 0.0609 0.0534 -	0.0733 0.0724 0.0609 0.0534 -	0.0489 0.0483 0.0463 0.0425 -	0.0424 0.0419 0.0405 0.0365 -	0.0424 0.0419 0.0405 0.0365 -	0.0424 0.0419 0.0405 0.0365 -
5	C907 [C907] [C907] [C907]	0.22	RT 400 800 1200 1600	79.00 78.18 77.26 75.89 -	1.2046 1.2172 1.2317 1.2539 -	1.2046 1.2172 1.2317 1.2539 -	2.4092 2.4344 2.4634 2.5078 -	5.8042 5.9263 6.0683 6.2891 -	350.40 321.77 234.98 120.71 15.625	11.930 11.186 8.164 4.153 -	10.350 9.5044 7.247 3.6531 -	6.9038 6.4733 4.8405 2.5771 -	5.9896 5.6160 4.1995 2.2358 -	0.2557 0.2348 0.1793 0.0964 -	0.2218 0.2060 0.1555 0.0828 -
6	TZM [TIC] [TIC] [TIC]		RT 400 800 1200 1600		2.1187 2.2518 2.4373 2.6561 2.9181	1.4787 1.4918 1.5381 1.5903 1.6527	3.5974 3.7436 3.9754 4.2464 4.5708	12.941 14.013 15.804 18.032 20.892	1.304 1.183 1.021 0.819 0.561	0.0990 0.0872 0.0751 0.0666 0.0587	0.0859 0.0843 0.0751 0.0666 0.0587	0.0573 0.0563 0.0541 0.0501 0.0435	0.0497 0.0489 0.0475 0.0435 0.0345	0.0497 0.0489 0.0475 0.0435 0.0345	0.0497 0.0489 0.0475 0.0435 0.0345
7	TiC [TiC] [TiC] [TiC]	0.25	RT 400 800 1200 1600	63.40 62.84 60.95 58.95 56.73	1.4787 1.4918 1.5381 1.5903 1.6527	1.4787 1.4918 1.5381 1.5903 1.6527	2.9574 2.9836 3.1346 3.1806 3.3054	8.7462 8.9019 9.8257 10.116 10.926	3.4850 3.0163 2.1655 1.5159 0.85074	2.1716 1.4339 0.853 0.7208 0.0395	1.8840 1.2432 0.578 0.7792 0.0342	$H_{90} = 1.2567$ $H_{75} = 0.8293$ $H_{25} = 0.3387$ $H_{90} = 0.1196$ $H_{75} = 0.0228$	1.0903 0.7194 0.2939 0.1036 0.0198	0.0465 0.0307 0.0121 0.0044 0.0007	0.0404 0.0266 0.0108 0.0036 0.0007
	Mo-TZM	0.30	RT 400 800 1200 1600	42.95 40.41 37.33 34.24 31.19	2.1187 2.2518 2.4373 2.6561 2.9181	2.1187 2.2518 2.4373 2.6561 2.9181									

Notes: (a) Use strength of weaker material (Mo-TZM) when dissimilar materials are used (pairs 1, 2, 4, and 6)

(c) $W_{ox} = 0.8678$ P_x

(d) $P_{75} = 0.5787$ P_{90}

(e) $P_{25} = 0.0214$ P_{90}

(f) All loads marked out with an X indicate those loads not to be used in the test program.

TABLE XV. SUMMARY OF FRICTION AND WEAR TESTS CONDUCTED IN HIGH VACUUM

Assembly No.	Arm No.	Test No.	Test Material		Test Temperature, °F		Speed SFM	Compressive Load Pounds (% 0.2% CYS or UCS)		Test Duration Minutes	Chamber Pressure, Torr		Average Coefficient of Friction	Wear Scar Diameter (1) Hemispherical Rider, Inch	Remarks
			Rider	Disc	Start	Finish		Start	Maximum		Start	Maximum			
I	1	500905A	Carboloy 907	Carboloy 907	RT	1020	500	11,830	90	9:25	9.5×10^{-9}	$1.7 \times 10^{-8}(2)$	0.78	0.22	Test terminated due to excessive wear of rider.
I	4	500K05A	Carboloy 907	Carboloy 907	RT	90	500	0.141	K(1)	60:00	5.5×10^{-9}	$9.4 \times 10^{-9}(2)$	0.78	N11	-----
II	1	400905A	Mo-TZM	Carboloy 907	RT	180	500	0.084	90	60:00	7.0×10^{-9}	$1.65 \times 10^{-8}(2)$	-- (6)	0.08	-----
II	3	500705A	Carboloy 907	Carboloy 907	RT	300	500	6.90	75	2:00	6.5×10^{-9}	$1.2 \times 10^{-8}(2)$	0.66	0.22	Test terminated due to slippage in magnetic drive.
II	4	404905A	Mo-TZM	Carboloy 907	400	400	500	0.081	90	60:00	3.3×10^{-9}	$1.0 \times 10^{-8}(2)$	-- (6)	0.05	Friction coefficient rose from 1 at start to 5 at end of test.
IV	1	504K05A	Carboloy 907	Carboloy 907	400	425	500	0.081	K(1)	60:00	7.2×10^{-9}	$9.8 \times 10^{-9}(4)$	(6)	N11	Friction coefficient rose from 0.4 at start to 5 at end of test.
IV	2	500705B	Carboloy 907	Carboloy 907	RT	915	500	6.90	75	60:00	3.2×10^{-10}	$8.5 \times 10^{-9}(4)$	0.37	0.22	-----
V	1	512705A	Carboloy 907	Carboloy 907	1200	1280	500	2.58	75	15:00	5.9×10^{-9}	$8.8 \times 10^{-9}(4)$	0.78	0.03	Test terminated due to slippage in magnetic drive
V	3	512H05A	Carboloy 907	Carboloy 907	1200	1295	500	0.117	H(5)	60:00	7.4×10^{-9}	$7.6 \times 10^{-9}(4)$	1.56	N11	Friction coefficient varied from 0.5 to 3 during test.
VI	1	300705A	7178	7178	RT	150	500	6.11	75	1:00	1.0×10^{-9}	$1.0 \times 10^{-9}(4)$	0.53	0.03	Disc fractured upon application of load.
VI	2	200K05A	7178	Mo-TZM	RT	103	500	0.080	K(3)	60:00	8.0×10^{-10}	$9.0 \times 10^{-10}(4)$	-- (6)	0.09	Friction coefficient decreased from 12 at start to 0.75 at end of test.

(1) Maximum Wear Scar Diameter = 0.250 Inch.

(2) Main Shaft Angular Contact Ball Bearings (MRC-7207) Lubricated with MoS₂.

(3) Constant Load = 90% of 0.2% CYS of Mo-TZM Alloy in Pairs 1 and 2.

(4) Main Shaft Angular Contact Ball Bearings (MRC-7207) Ultrasonically Cleaned and Unlubricated.

(5) Constant Load = 75% of UCS of TiC+10%Zn in Pair 7.

(6) Coefficient of Friction Values are not Considered Valid Because of Inaccuracies in Torque.

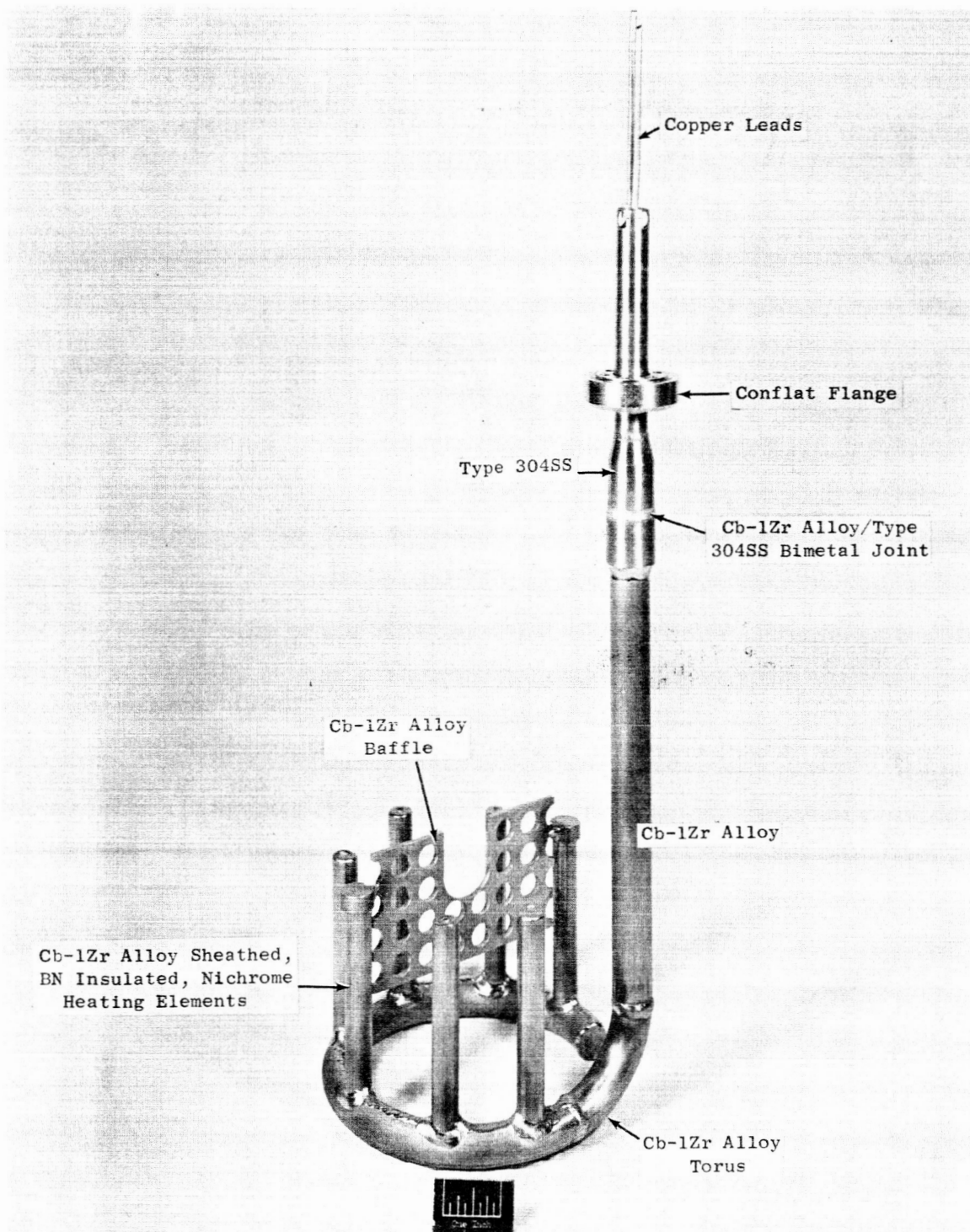


Figure 1. Conductive Immersion Heater Assembly for Potassium Friction and Wear Tester.

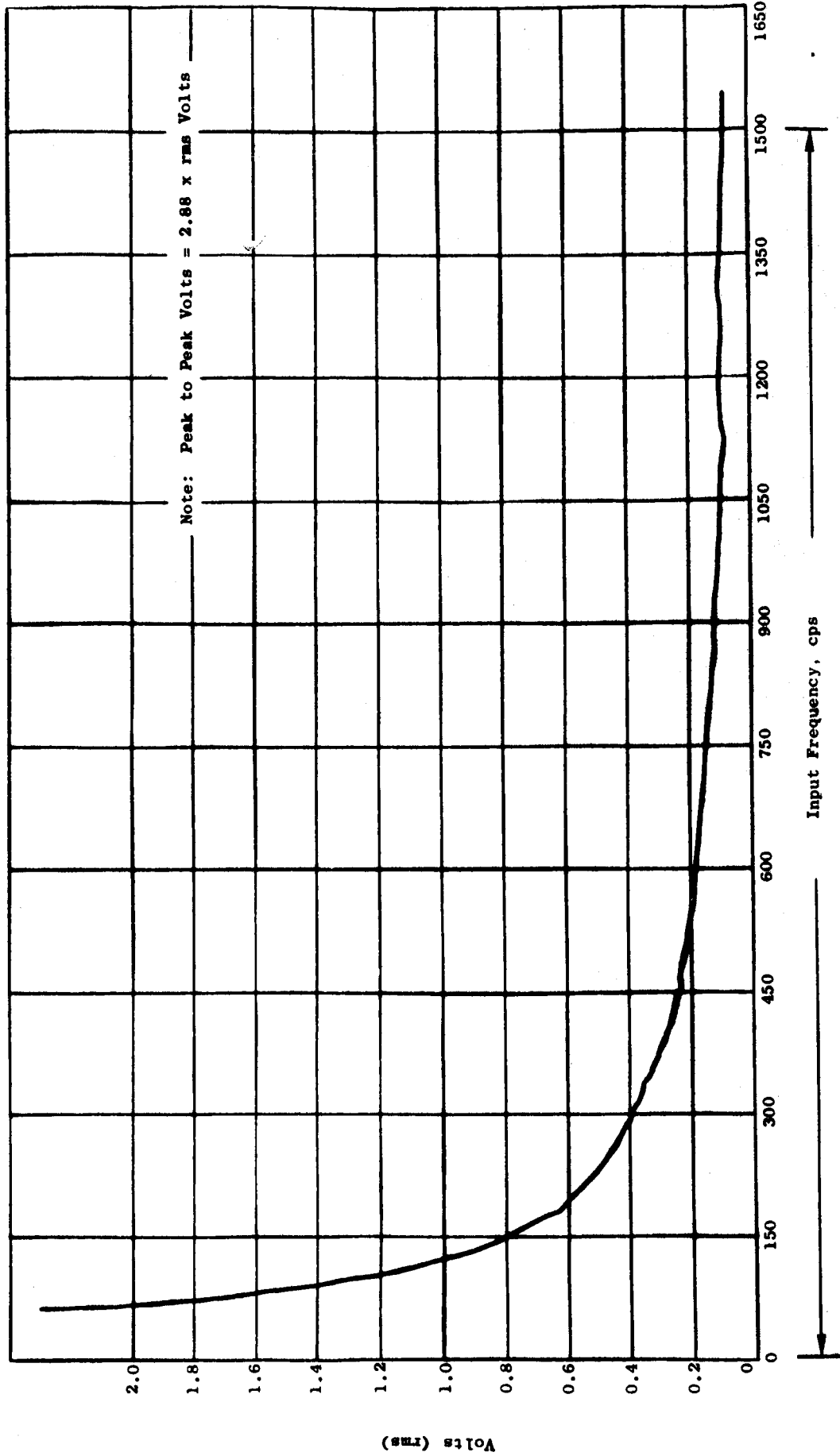
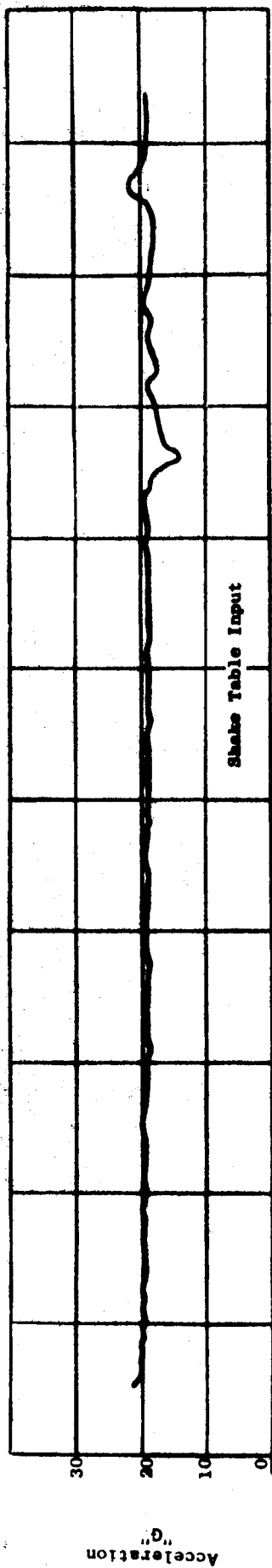


Figure 2. Calibration Curve for Vibration Pickup No. 2898.

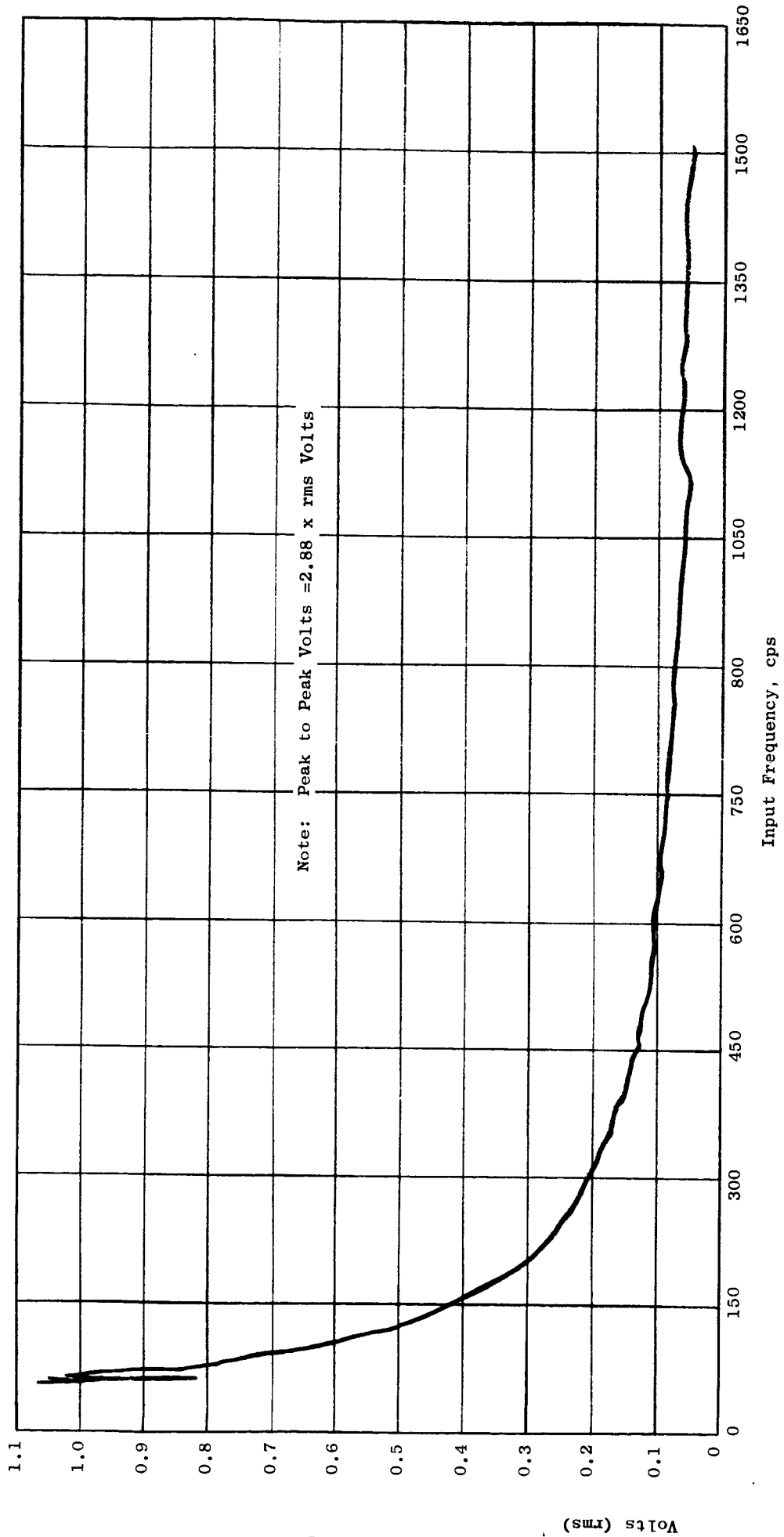
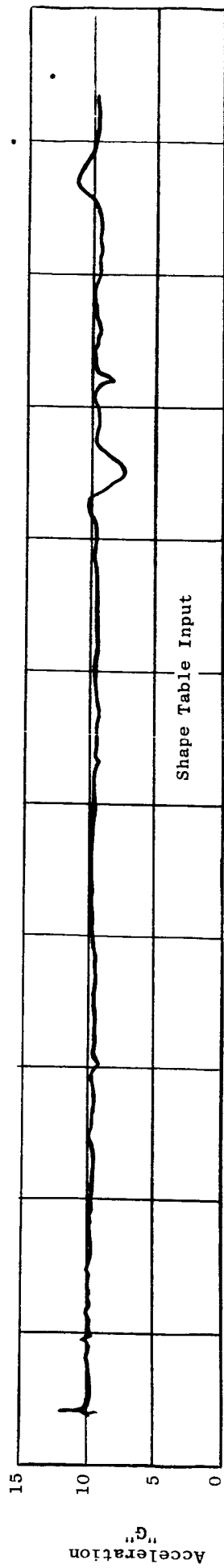


Figure 3. Calibration Curve for Vibration Pickup No. 5019.

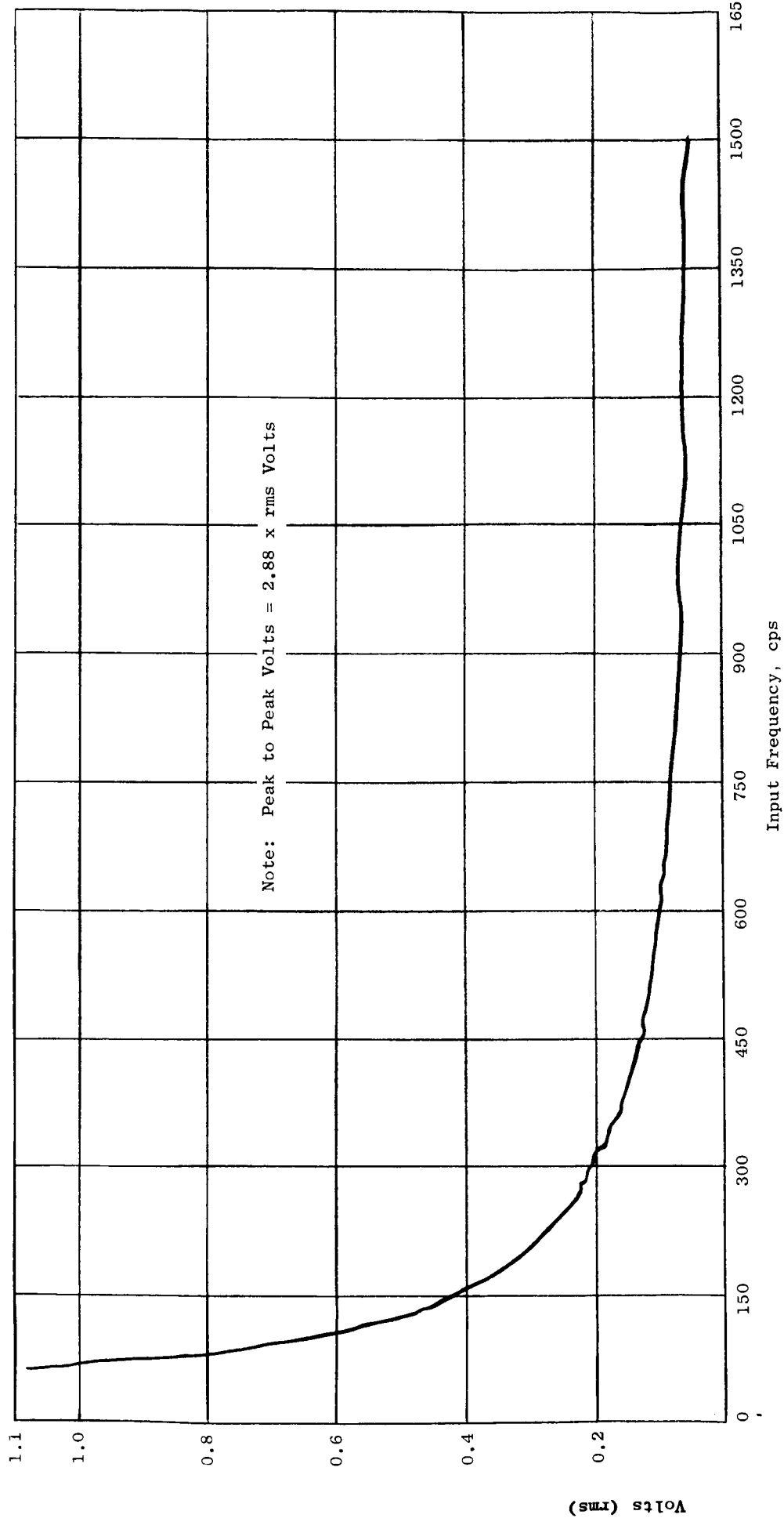
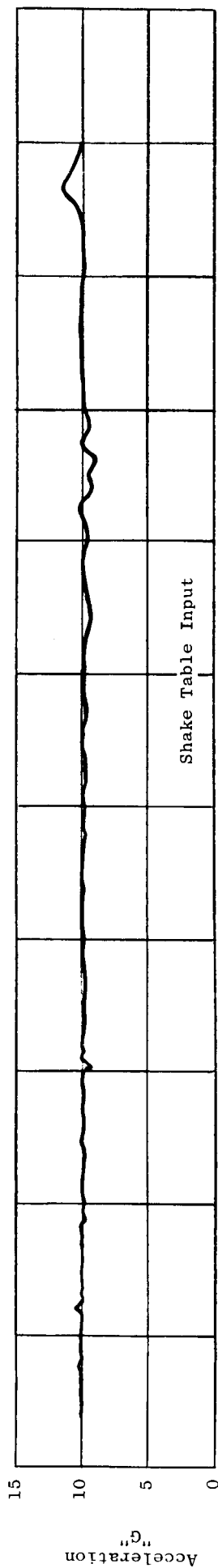


Figure 4. Calibration Curve for Vibration Pickup No. 4772.

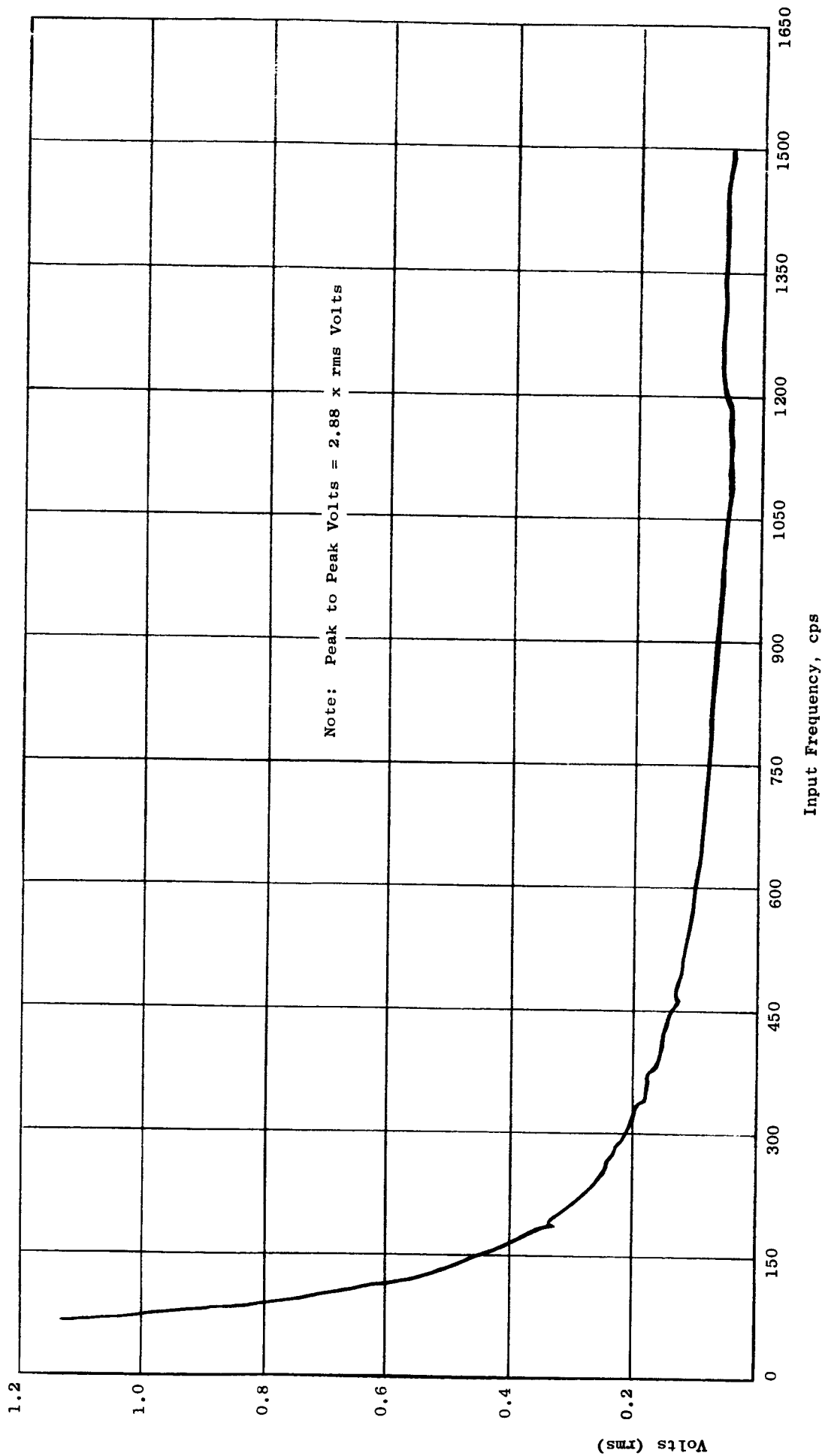
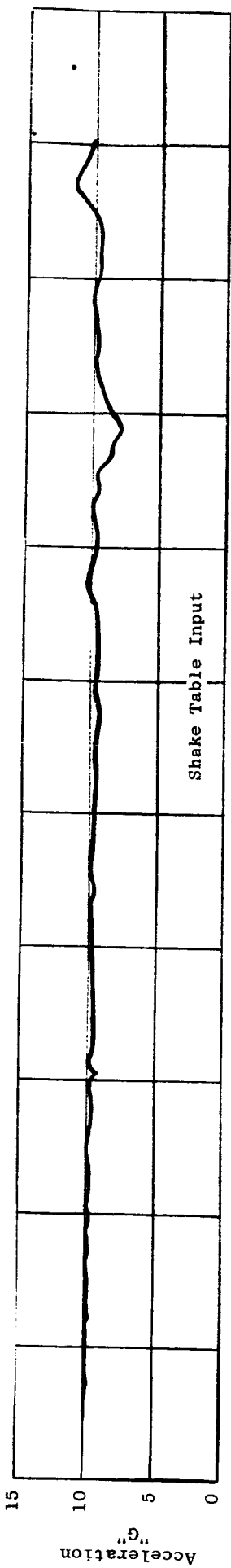


Figure 5. Calibration Curve for Vibration Pickup No. 4769.

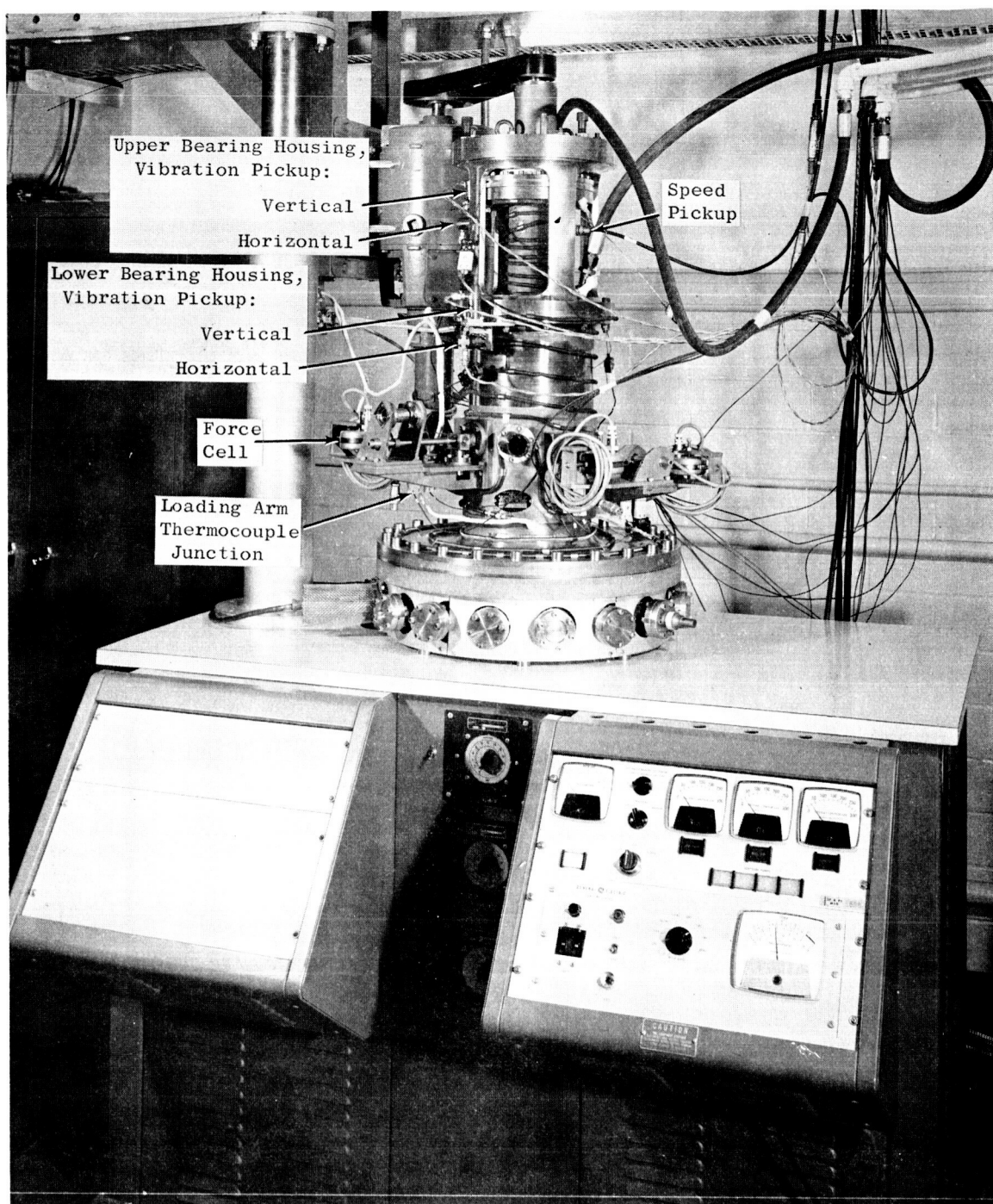


Figure 6. High Vacuum Friction Tester Fully Instrumented Prior to Test.

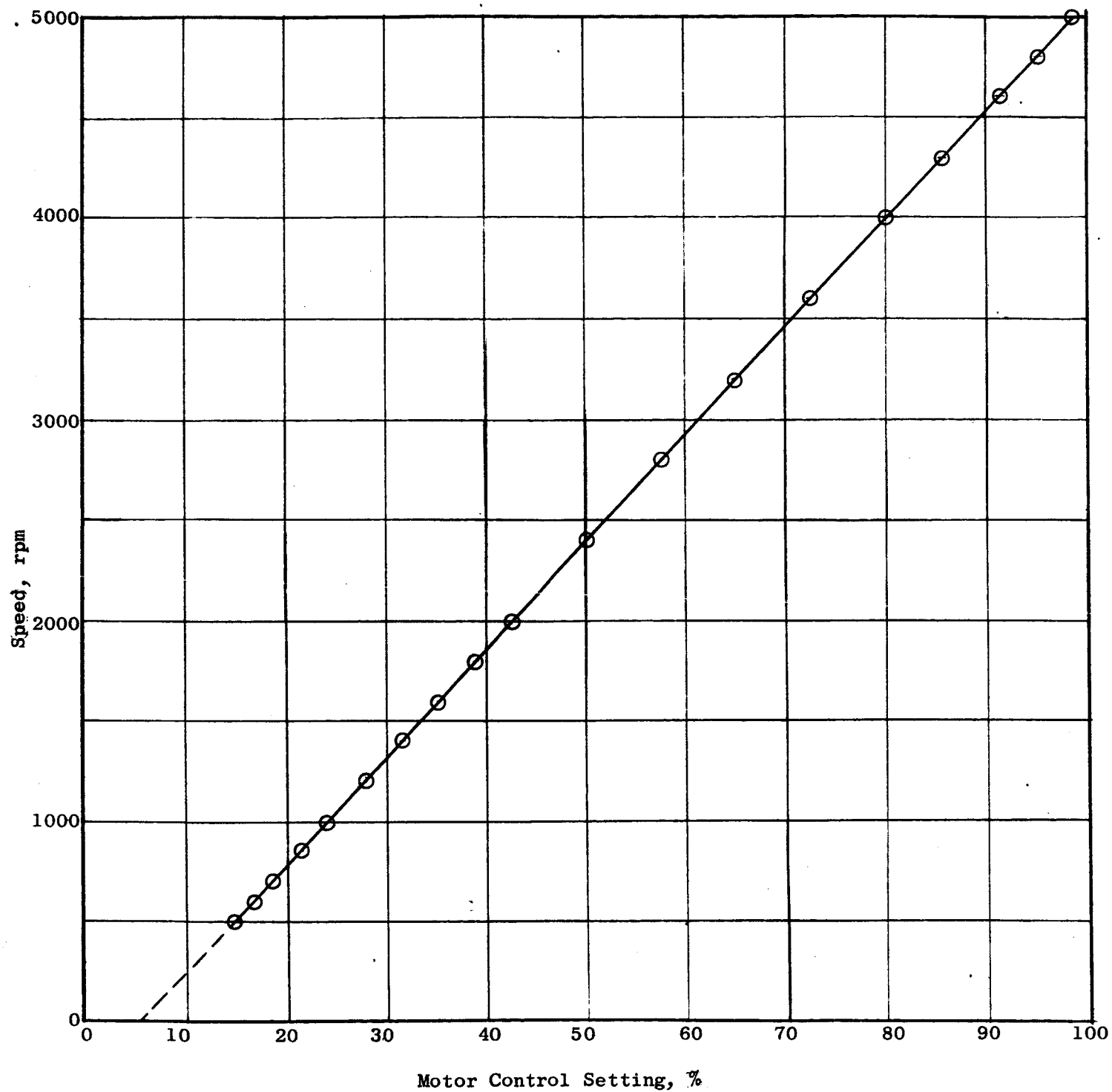


Figure 7. Speed Calibration of Electric Drive Motor Control Setting.

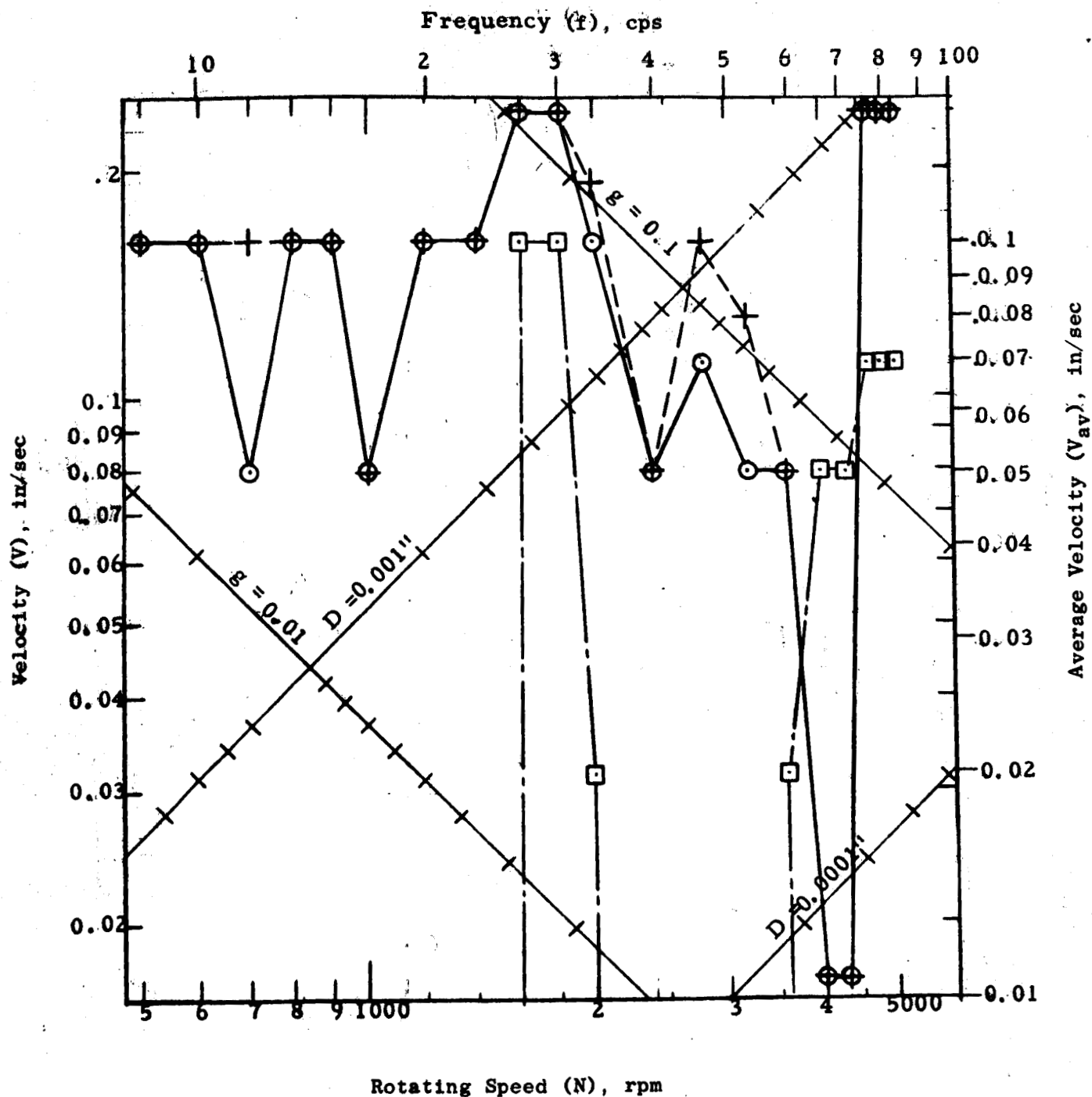


Figure 8. Vibration Performance of High Vacuum Friction and Wear Tester.

D = Peak-to-peak deflection, in.
g = Acceleration, gravity units

○ = Upper bearing, vertical
+ = Upper bearing, horizontal
□ = Lower bearing, vertical & horizontal

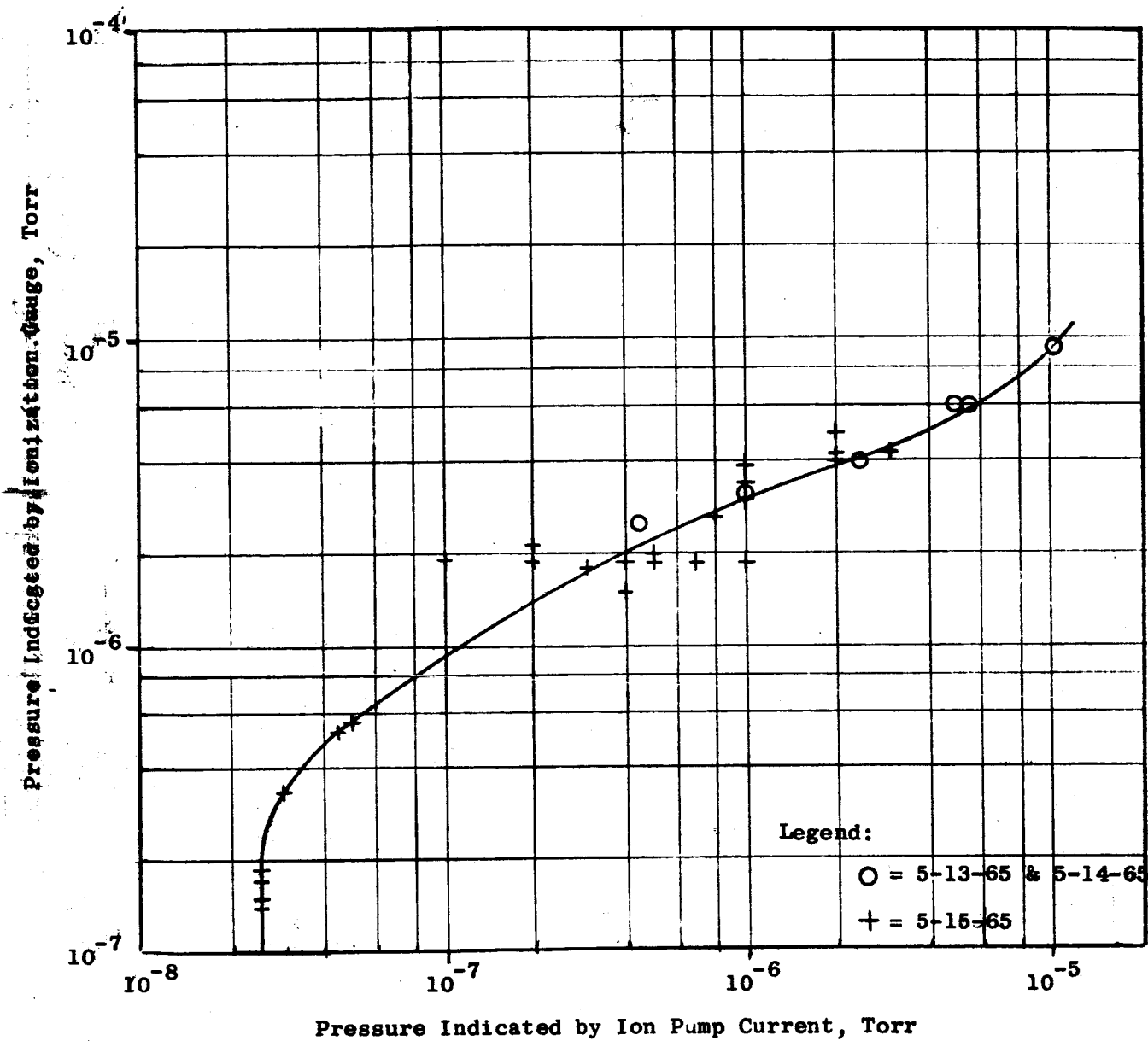


Figure 9. Correlation of Ionization Gauge Pressure with Pressure Indicated by Ion Pump Current.

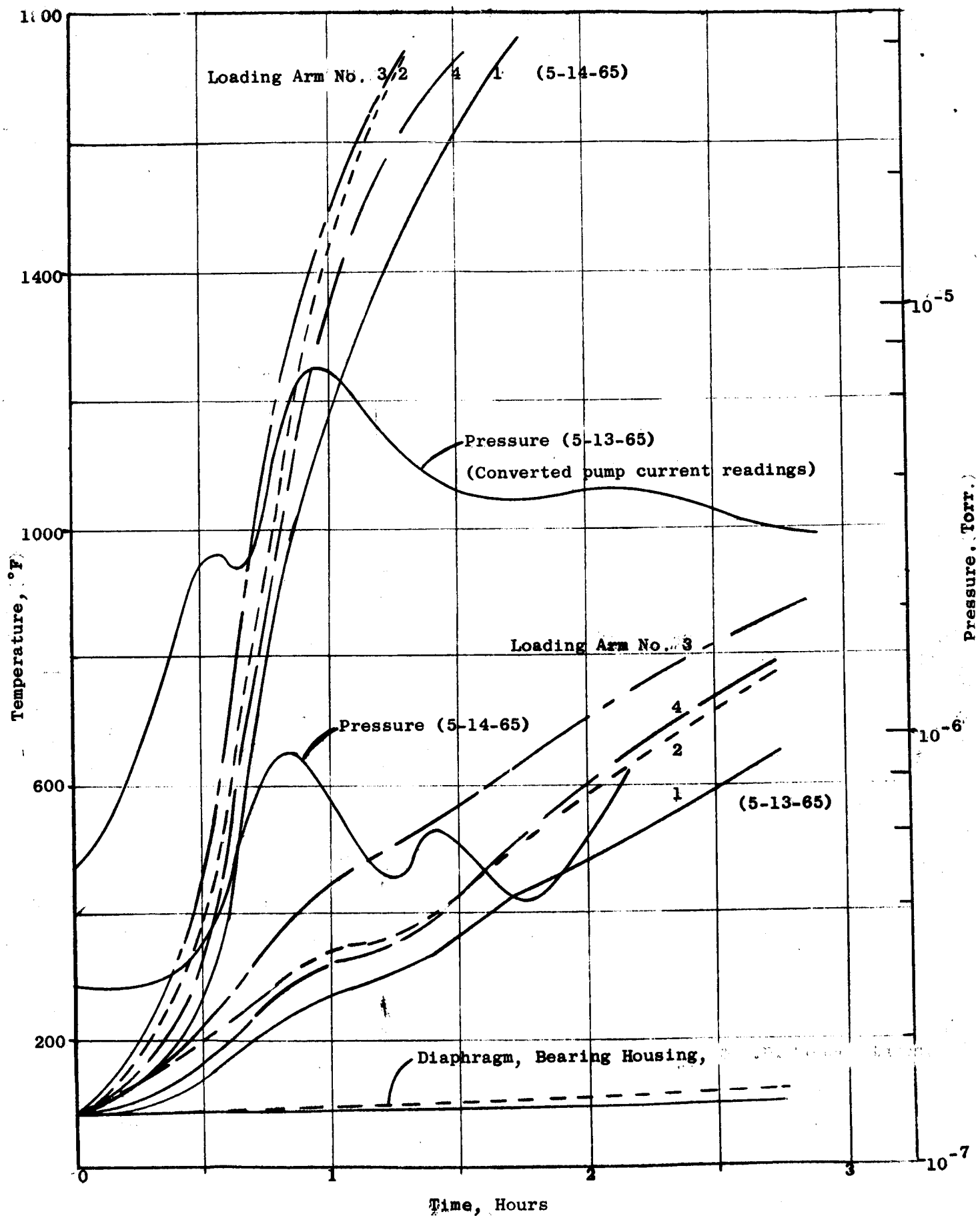


Figure 10. Change in Temperatures and Pressures During Specimen Heater Test.

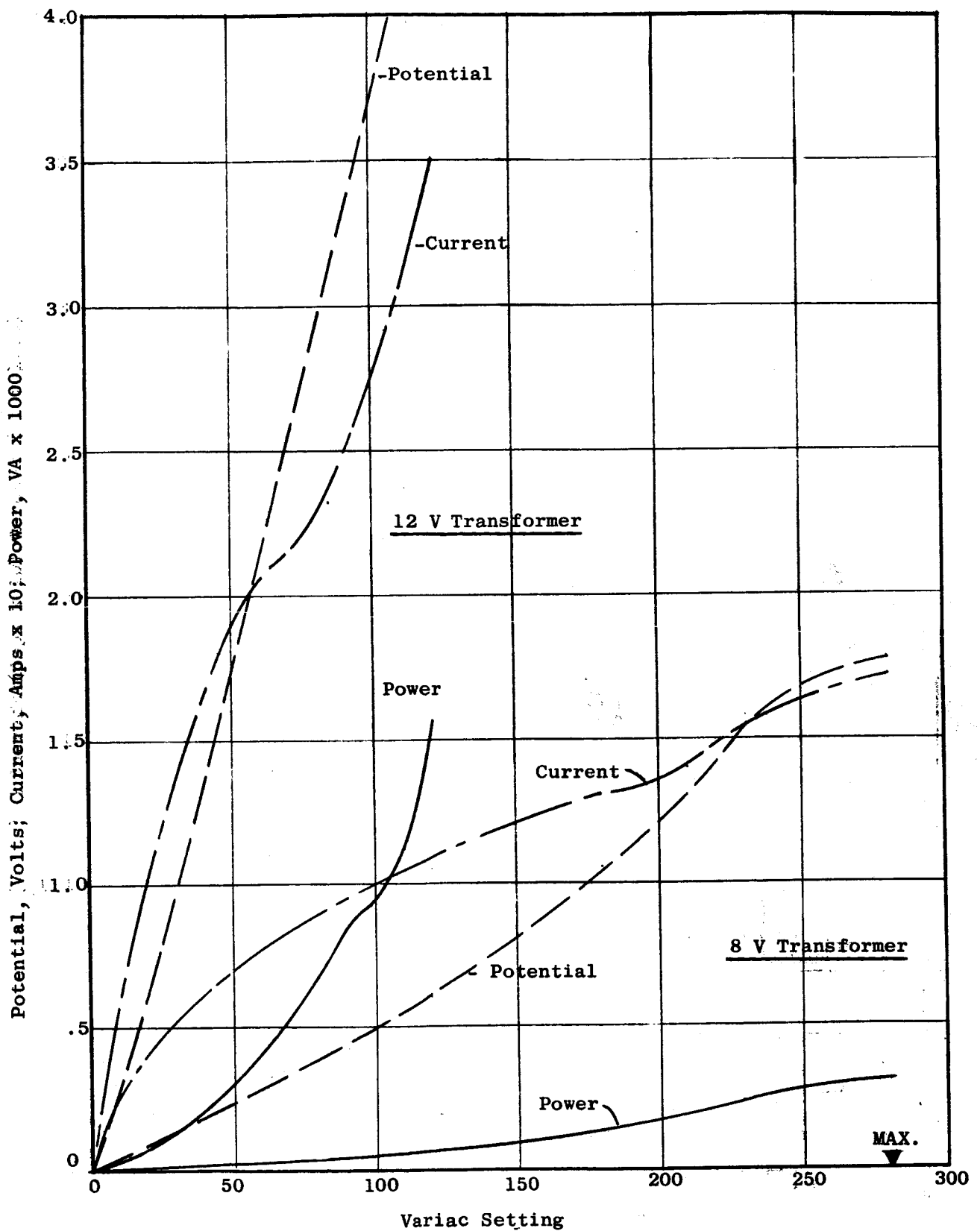


Figure 11. Performance Data for High Vacuum Friction and Wear Tester Specimen Heater.

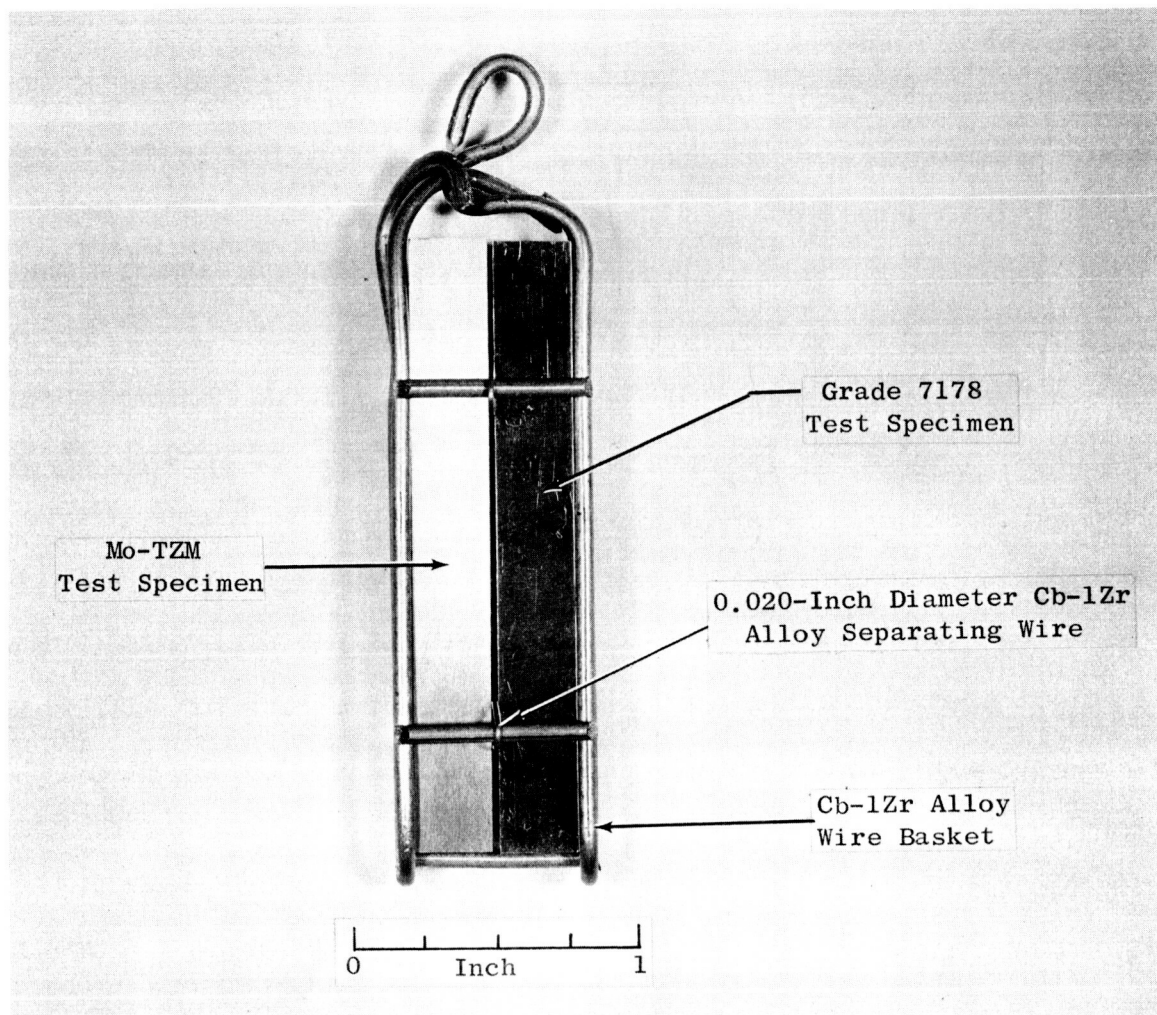


Figure 12. Mo-TZM Alloy and Grade 7178 Corrosion Test Specimens Prior to Being Inserted into a Cb-1Zr Alloy Capsule. The Cb-1Zr Alloy Wire Maintains Position and Spacing of the Specimens During the 1000-Hour Exposure to Potassium.

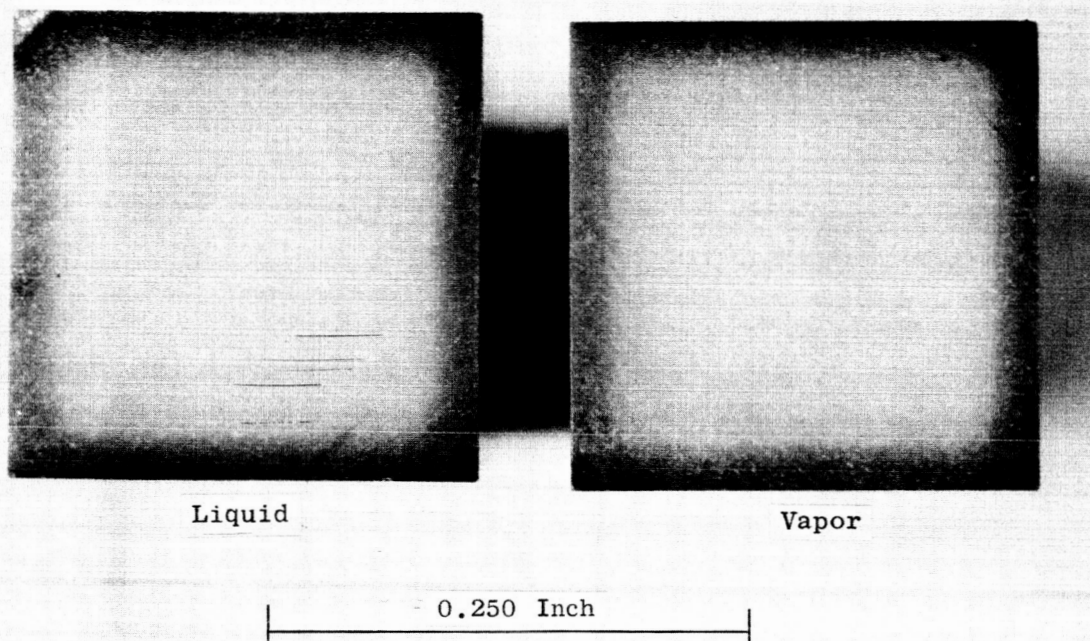
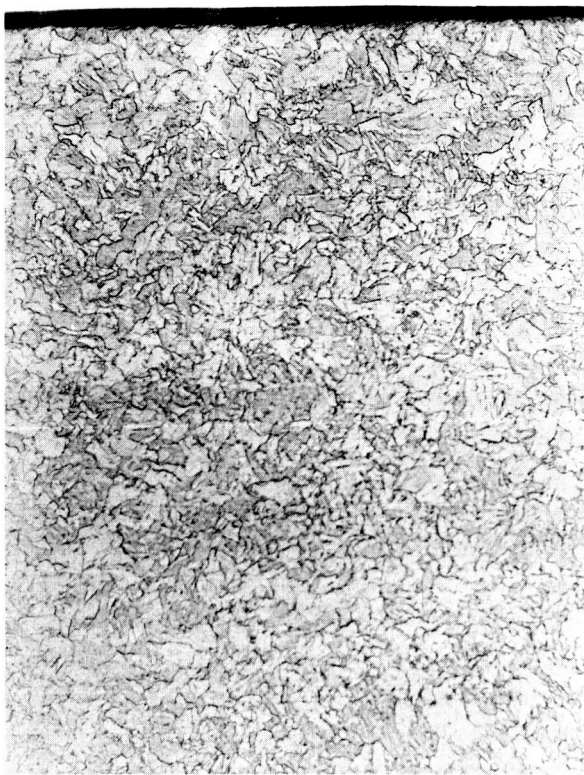
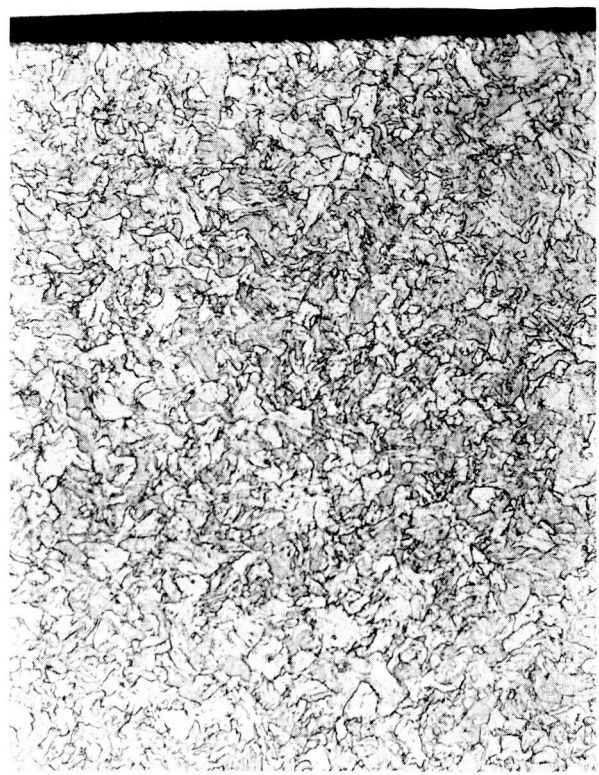


Figure 13. Sectioned Corrosion Specimens of Zircoa 1027 (95.5% ZrO_2) After Exposure to Potassium Liquid and Vapor for 1000 Hours at 800°F. (C65091240)

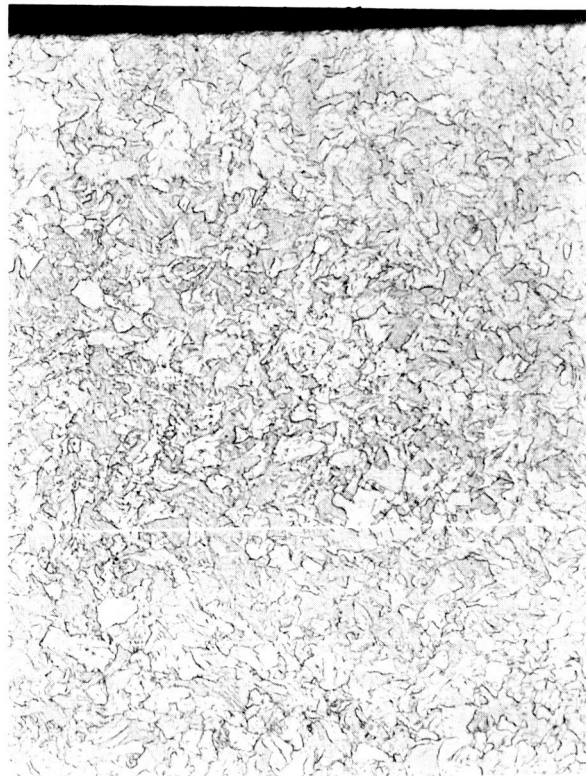


Post-Test Liquid Zone (A052121)



Post-Test Vapor Zone (A052221)

0 0.004
Inch



Pre-Test (A052111)

Figure 14. Microstructure of Transverse Section of Mo-TZM Alloy (Stress Relieved 2250°F 1/2 Hour) Before and After Exposure to Potassium Liquid and Vapor for 1000 Hours at 1600°F.
Etchant: 20% Murakamis

Mag: 250X

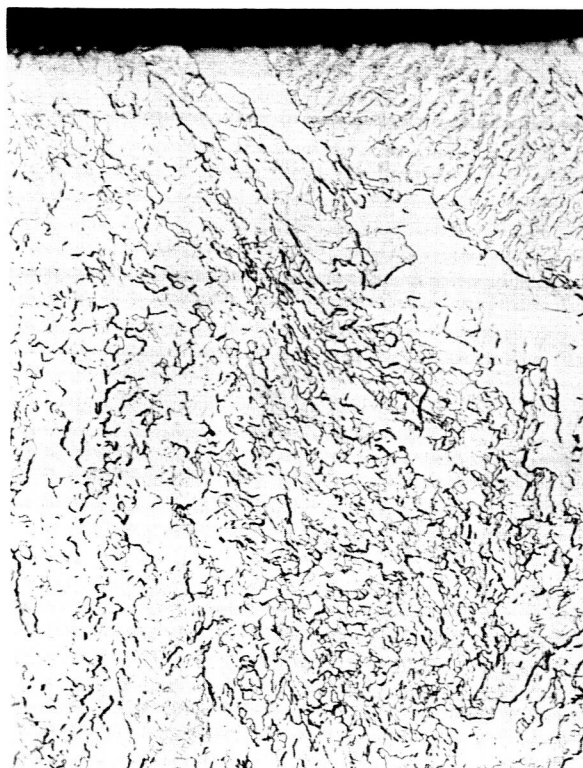


Post-Test Liquid Zone (A051321)



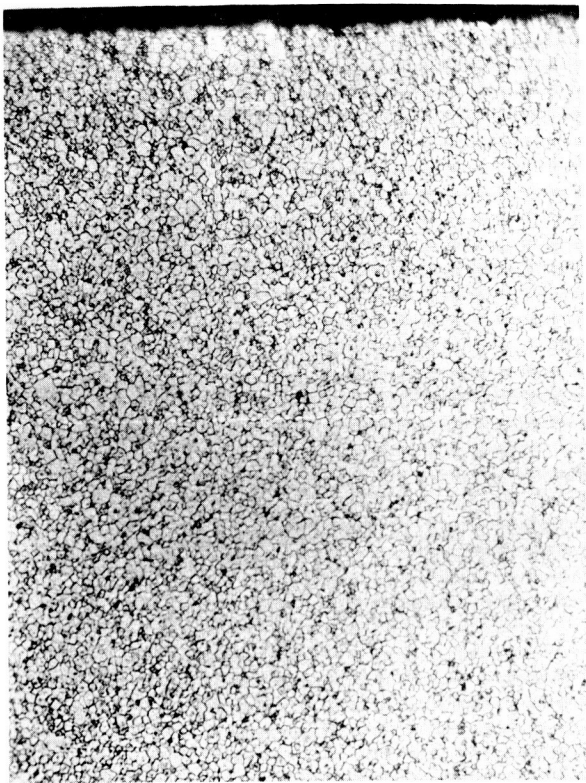
Post-Test Vapor Zone (A051421)

0 0.004
Inch

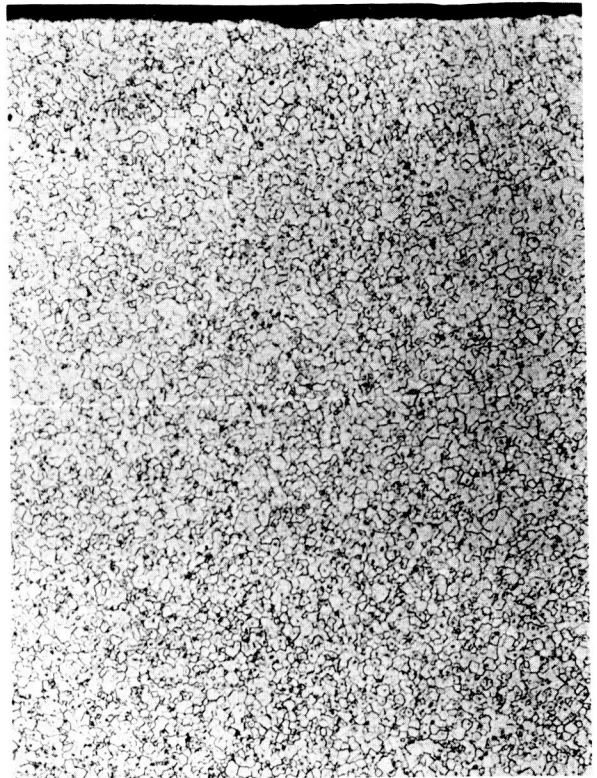


Pre-Test (A051311)

Figure 15. Microstructure of Transverse Section of Unalloyed Tungsten (Stress Relieved 2000°F One Hour) Before and After Exposure to Potassium Liquid and Vapor for 1000 Hours at 1600°F.
Etchant: 20% Murakamis Mag: 250X



Post-Test Liquid Zone (A050921)



Post-Test Vapor Zone (A051021)

0 0.004
Inch

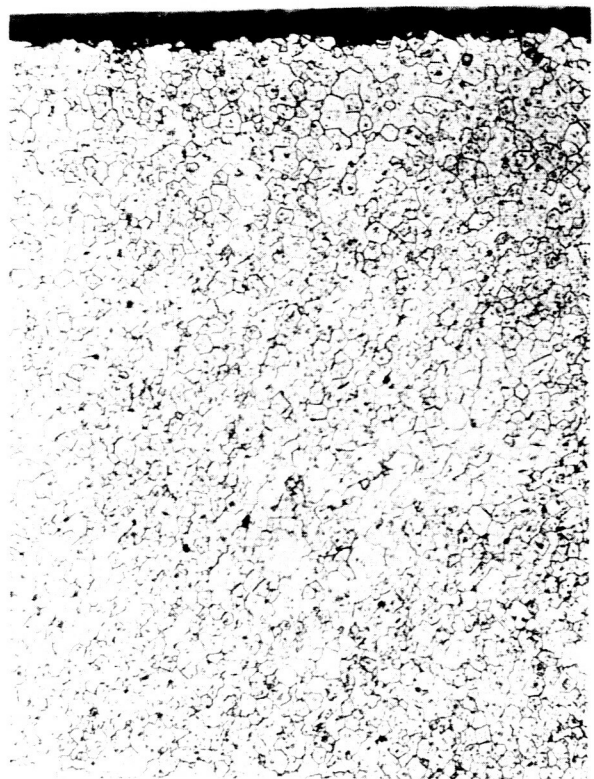


Pre-Test (A050911)

Figure 16. Microstructure of TiC+10%Mo Before and After Exposure to Potassium Liquid and Vapor for 1000 Hours at 1600°F.
Etchant: 80% HNO_3 +20% HF Mag: 250X

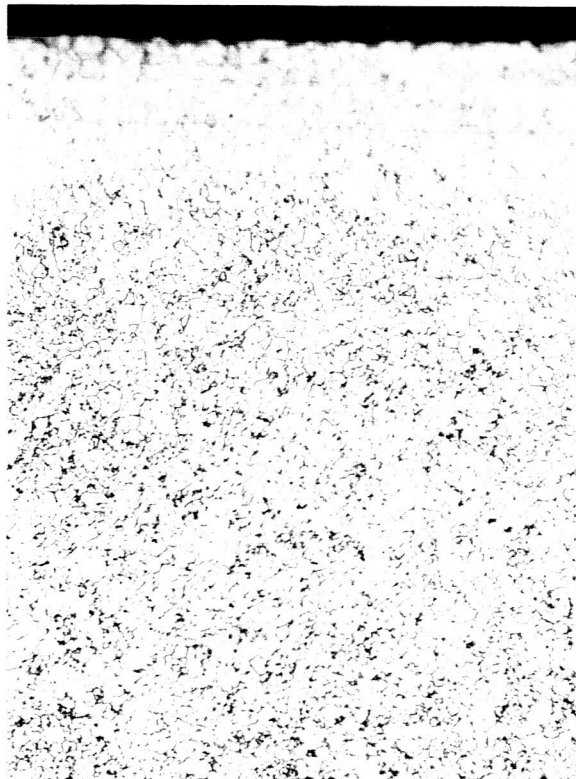


Post-Test Liquid Zone (A051721)



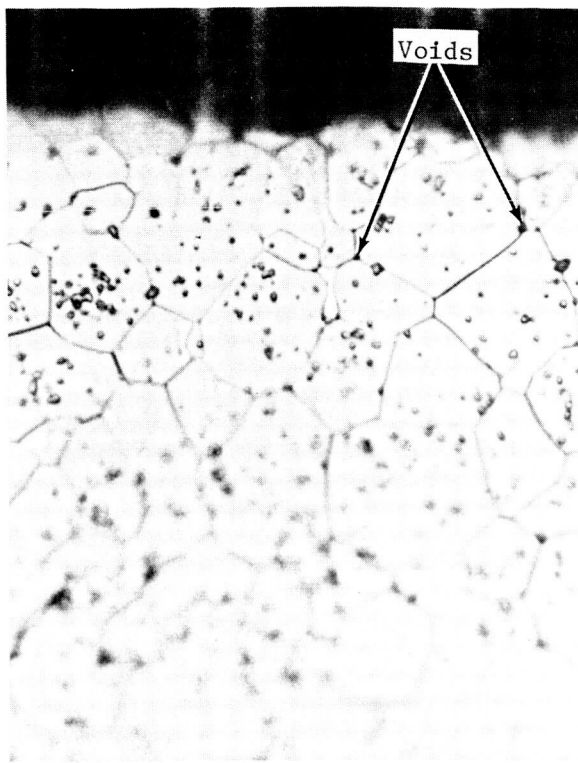
Post-Test Vapor Zone (A051821)

0 0.004
Inch

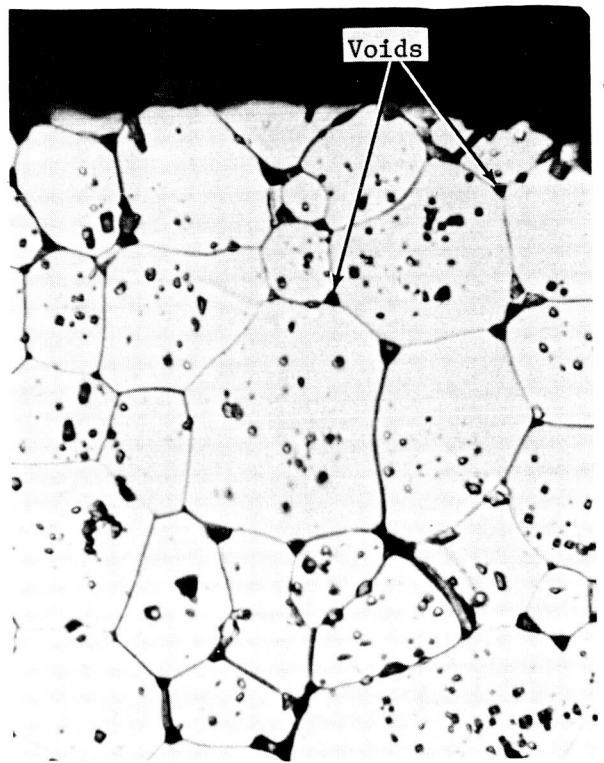


Pre-Test (A051711)

Figure 17. Microstructure of TiC+10%Cb Before and After Exposure to Potassium Liquid and Vapor for 1000 Hours at 1600°F.
Etchant: 80% HNO_3 +20% HF Mag: 250X

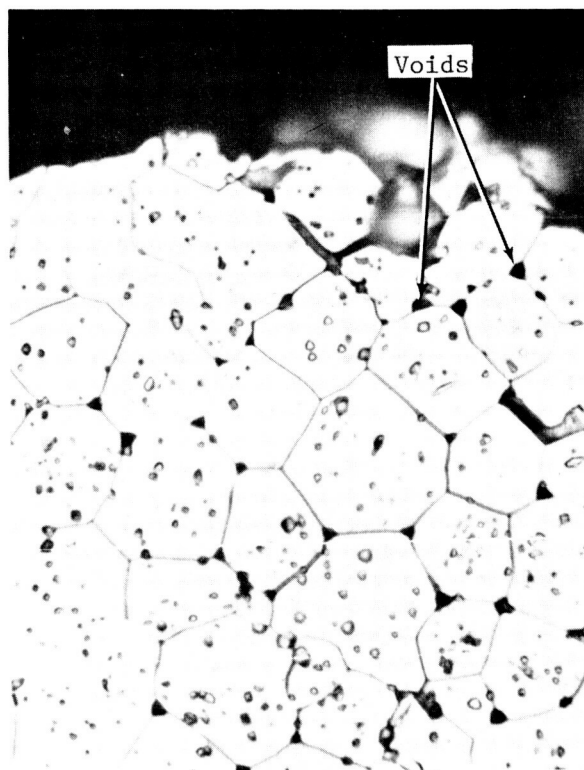


Post-Test Liquid Zone (A051723)



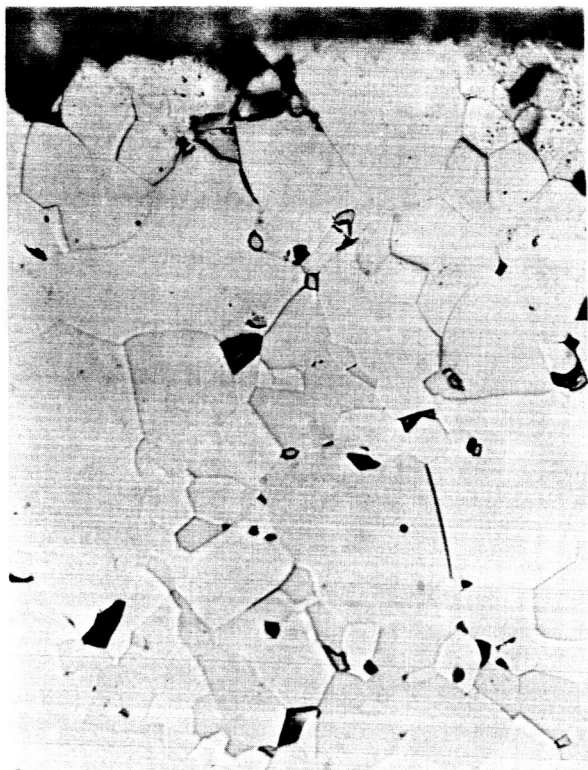
Post-Test Vapor Zone (A051823)

0 0.0005 0.001
Inch

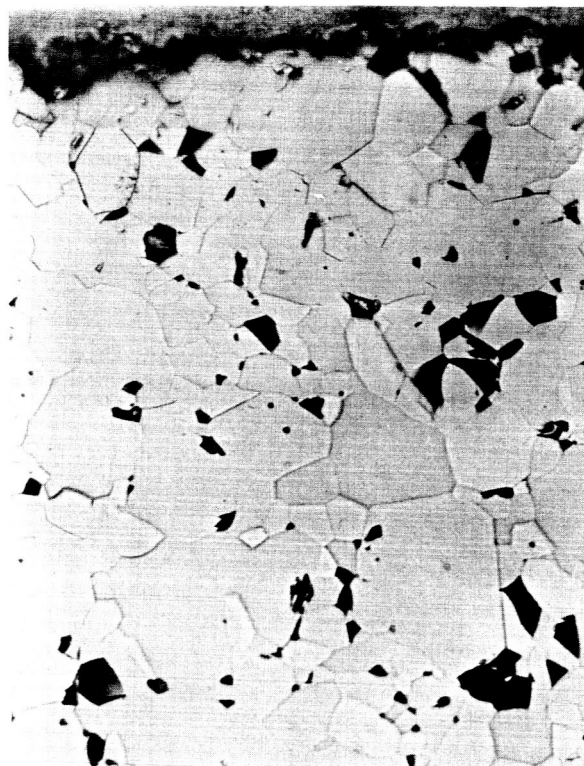


Pre-Test (A051813)

Figure 18. Microstructure of Tic+10%Cb Before and After Exposure to Potassium Liquid and Vapor for 100 Hours at 1600°F.
Etchant: 80% HNO_3 +20% HF Mag: 2000X

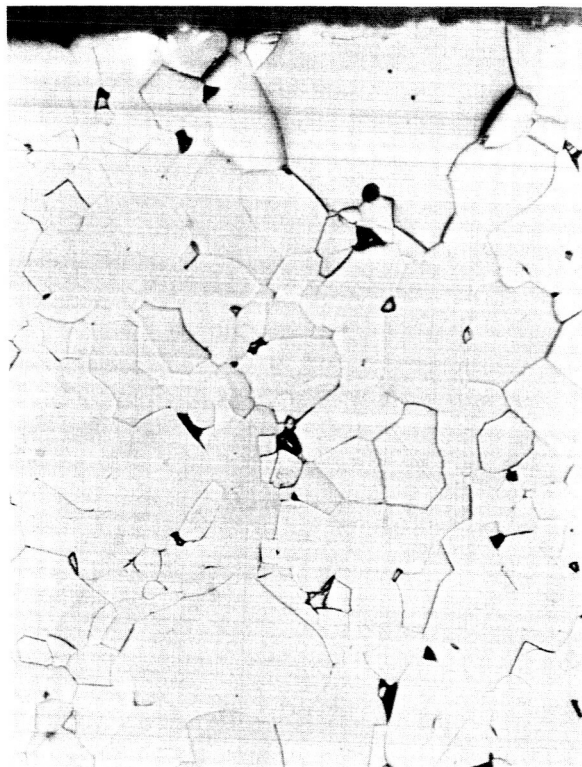


Post-Test Liquid Zone (A051121)



Post-Test Vapor Zone (A051221)

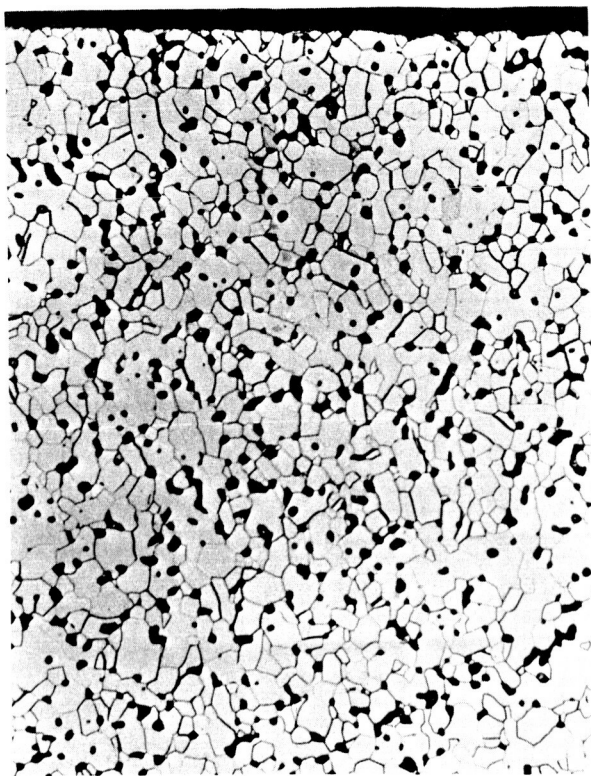
0 0.004
Inch



Pre-Test (A051111)

Figure 19. Microstructure of Lucalox (99.8% Al_2O_3) Before and After Exposure to Potassium Liquid and Vapor for 1000 Hours at 1600°F. Note: Apparent Porosity is a Combination of Pull Out During Polishing and Some Voids Enhanced by Etching.
Etchant: Boiling KF_2

Mag: 250X

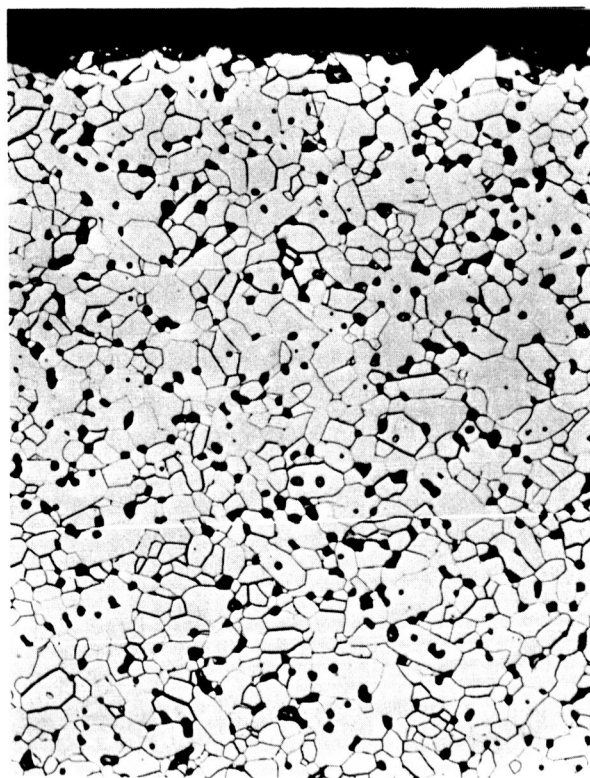


Post-Test Liquid Zone (A052521)



Post-Test Vapor Zone (A052621)

0 0.004
Inch

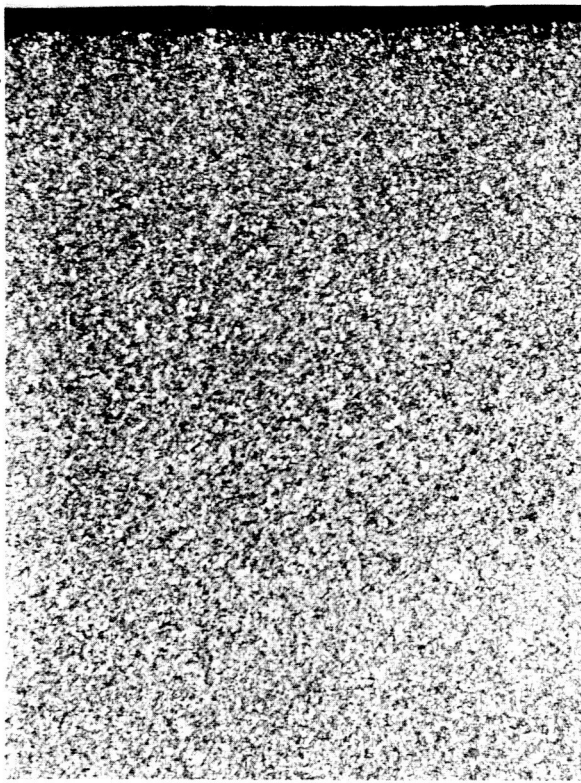


Pre-Test (A052511)

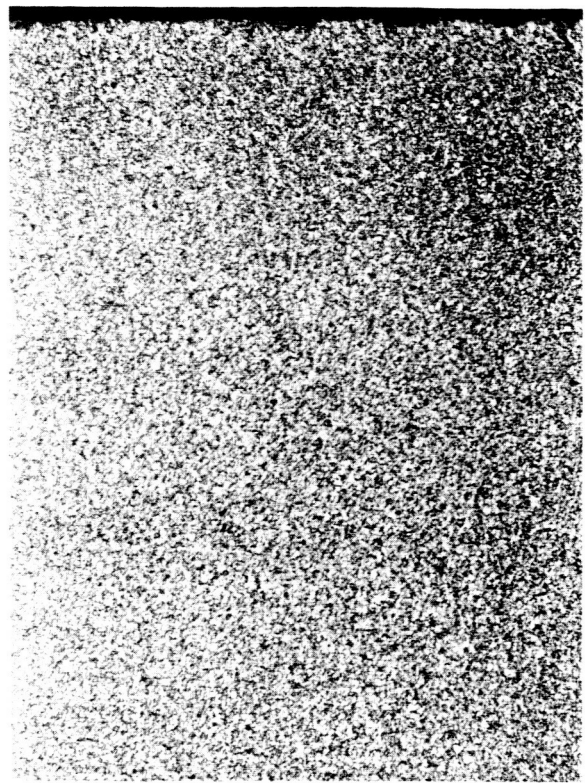
Figure 20. Microstructure of TiB_2 Before and After Exposure to Potassium Liquid and Vapor for 1000 Hours at 1600°F. Note: Apparent Porosity is a Combination of Pull Out During Polishing and Some Voids Enhanced by Etching.

Etchant: 1%Lactic Acid+1% HNO_3 +1%HF

Mag: 250X

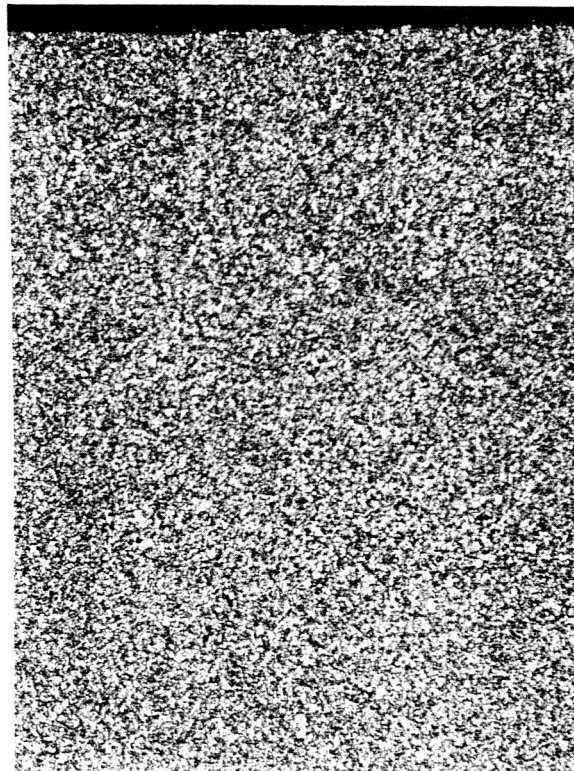


Post-Test Liquid Zone (A050321)



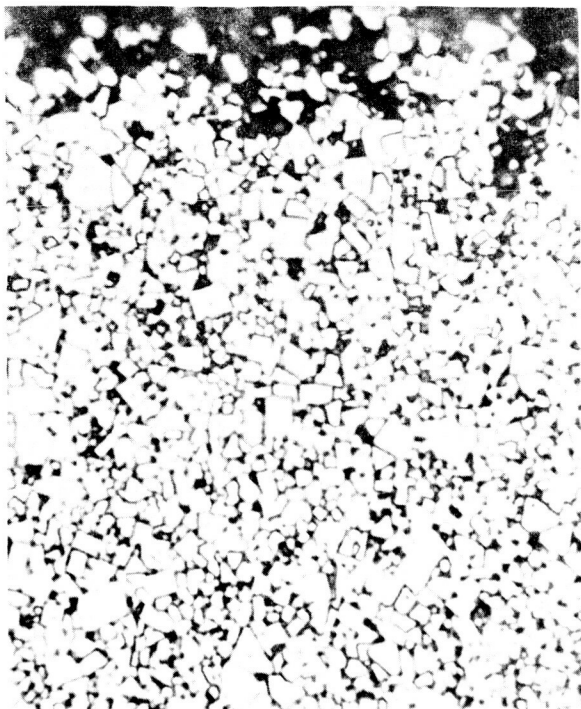
Post-Test Vapor Zone (A050421)

0 0.004
Inch

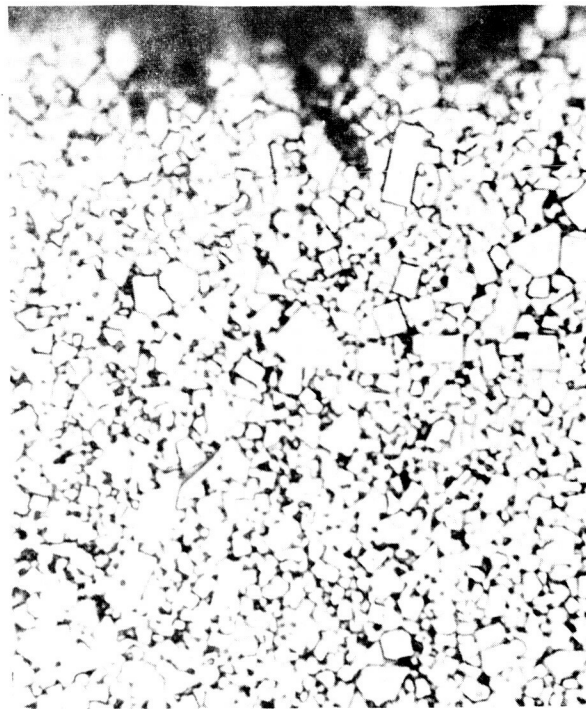


Pre-Test (A050311)

Figure 21. Microstructure of Carboloy 999 (97%WC-3%Co) Before and After Exposure to Potassium Liquid and Vapor for 1000 Hours at 1600°F.
Etchant: 10%NaOH, Electrolytic Mag: 250X

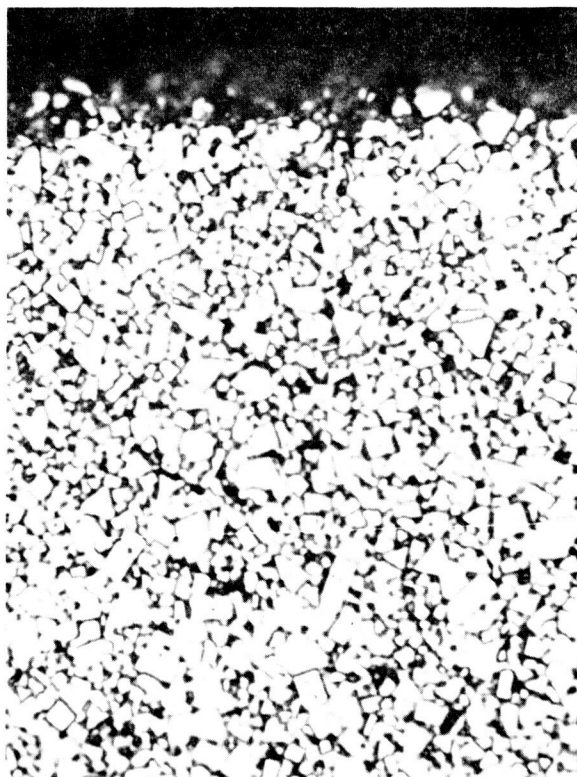


Post-Test Vapor Zone (A050423)
 Note Apparent Surface Attack
 to a Depth of 0.0004 Inch.



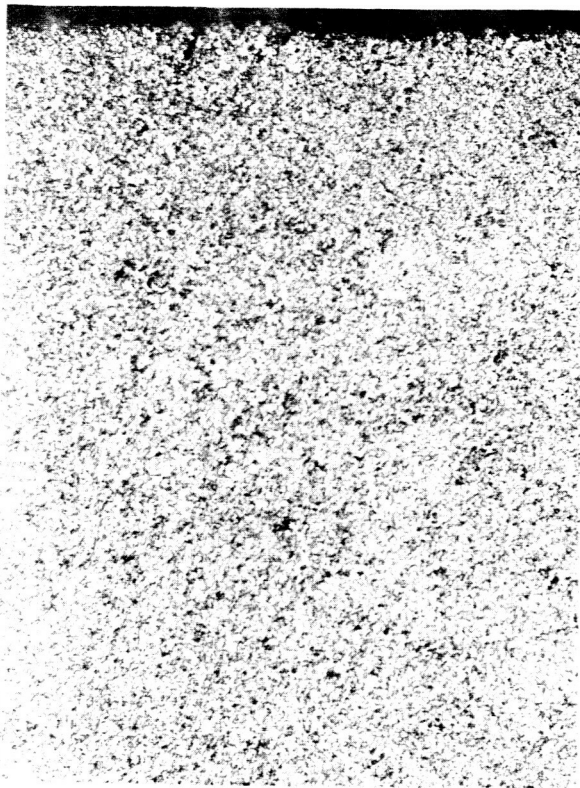
Post-Test Vapor Zone (A050423)
 Note Apparent Surface Roughening
 to a Depth of 0.0002 Inch.

0 0.0005 0.001
 └──────────┴──────────┴──────────┘
 Inch

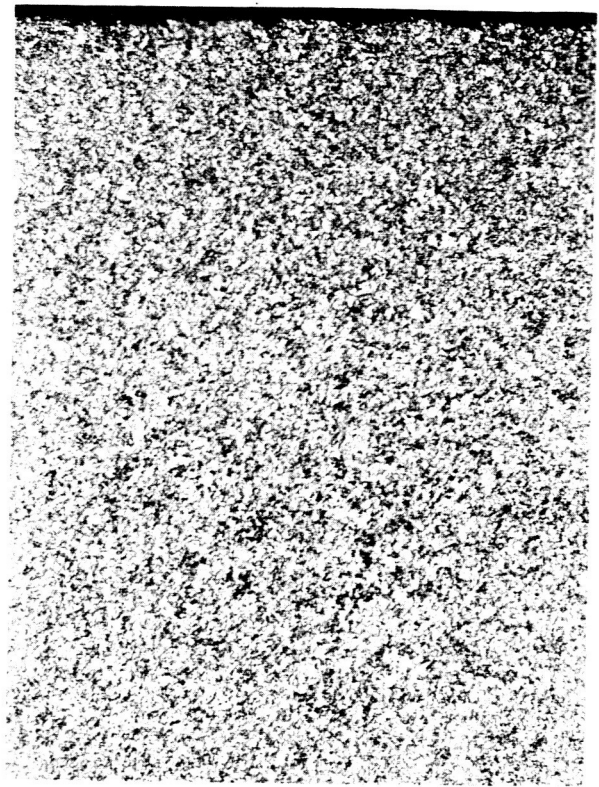


Pre-Test (A050313)

Figure 22. Microstructure of Carboloy 999 (97%WC-3%Co) Before and After
 Exposure to Potassium Liquid and Vapor for 1000 Hours at 1600°F.
 Etchant: 10%NaOH, Electrolytic Mag: 2000X

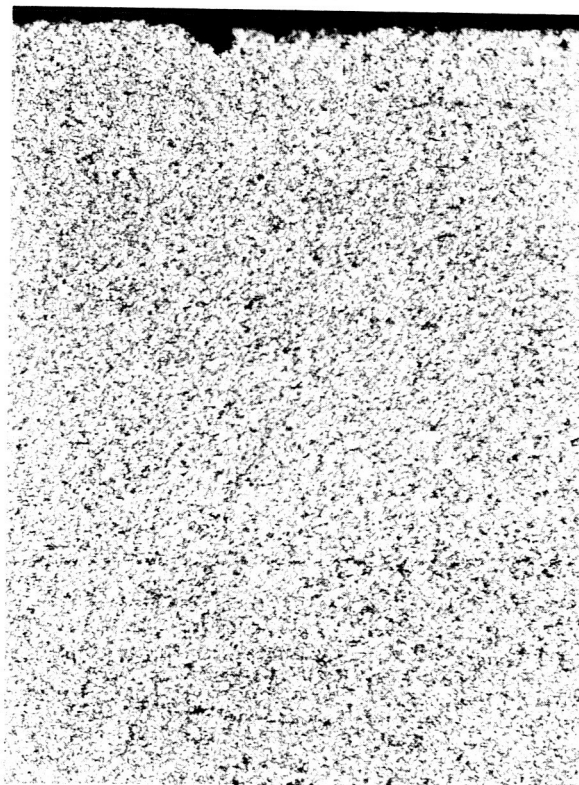


Post-Test Liquid Zone (A052321)



Post-Test Vapor Zone (A052421)

0 0.004
Inch

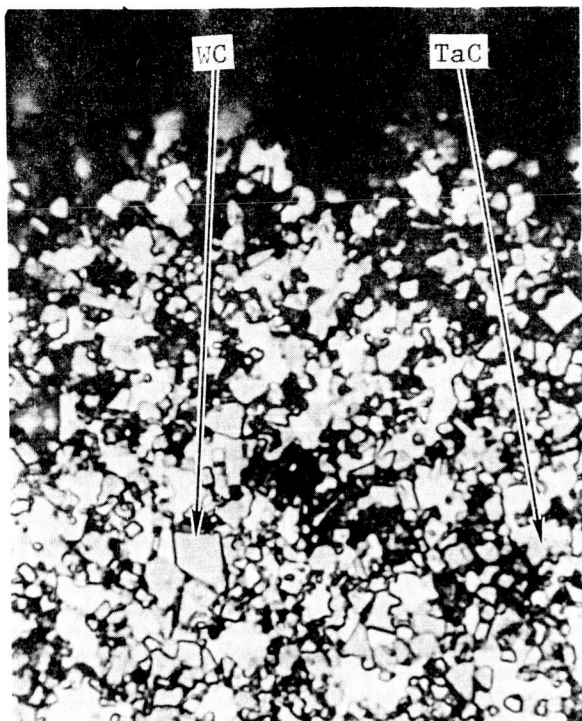


Pre-Test (A052311)

Figure 23. Microstructure of Carboloy 907 (74%WC-20%TaC-6%Co) Before and After Exposure to Potassium Liquid and Vapor for 1000 Hours at 1600°F.

Etchant: 10%NaOH, Electrolytic

Mag: 250X

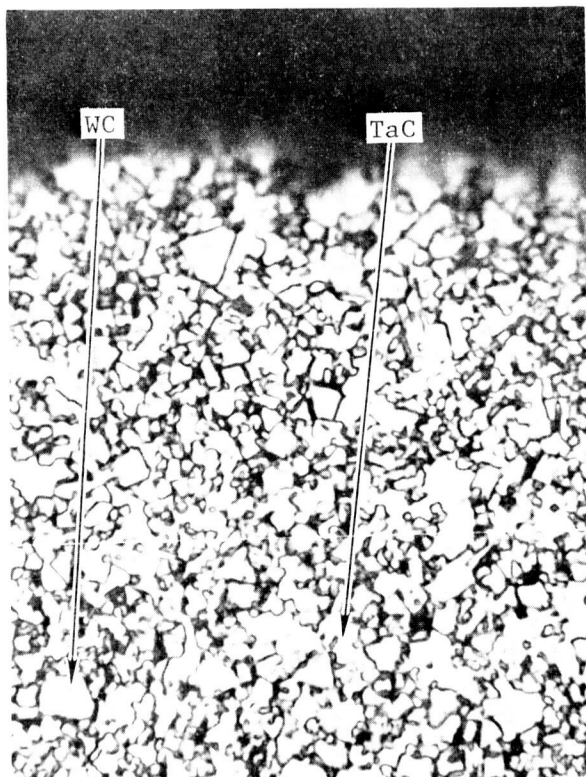


Post-Test Liquid Zone (A052323)
 Note Apparent Surface Attack
 to a Depth of 0.0007 Inch.



Post-Test Vapor Zone (A052423)
 Note Apparent Surface Roughening
 to a Depth of 0.0002 Inch.

0 0.0005 0.001
 Inch

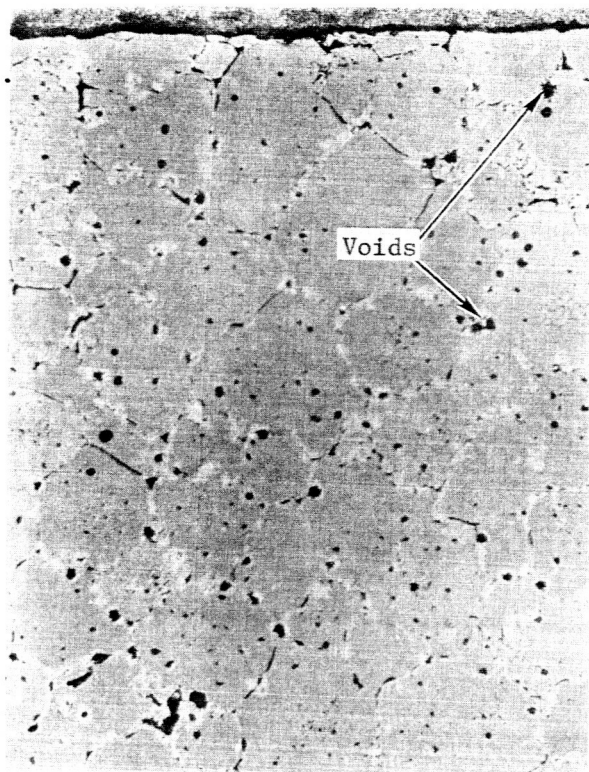


Pre-Test (A052313)

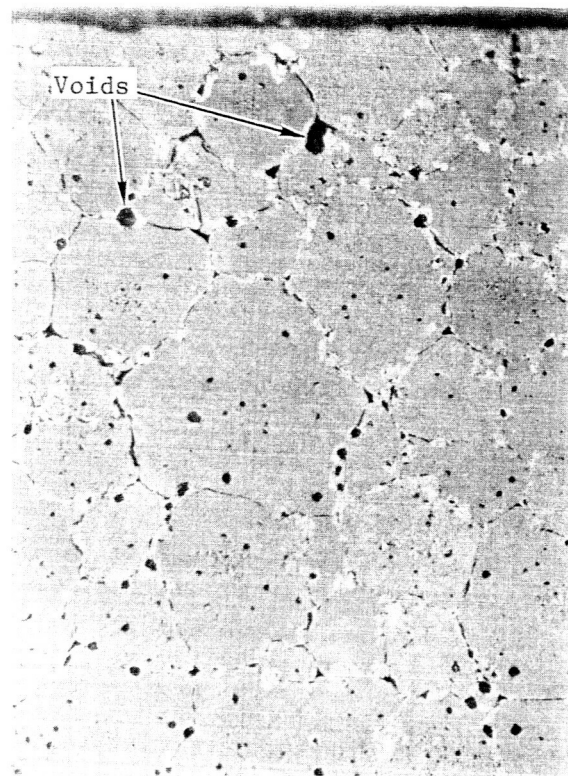
Figure 24. Microstructure of Carboloy 907 (74%WC-20%TaC-6%Co) Before and After Exposure to Potassium Liquid and Vapor for 1000 Hours at 1600°F.

Etchant: 10%NaOH, Electrolytic

Mag: 2000X

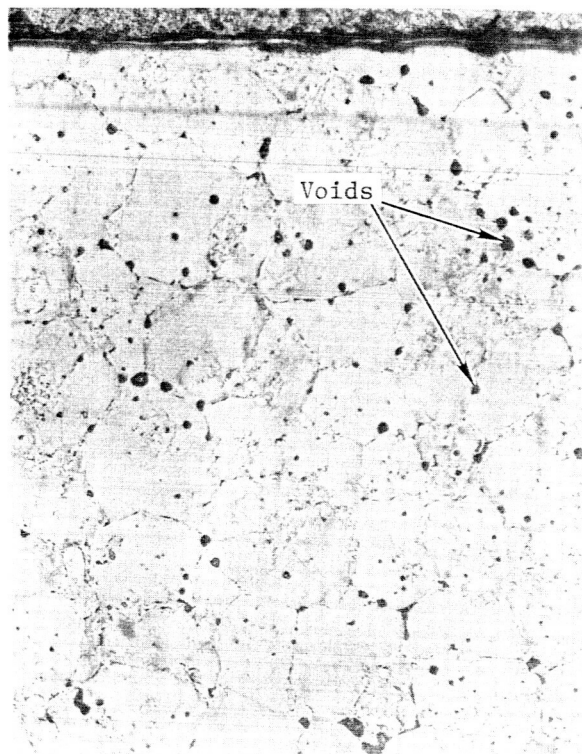


Post-Test Liquid Zone (A050121)



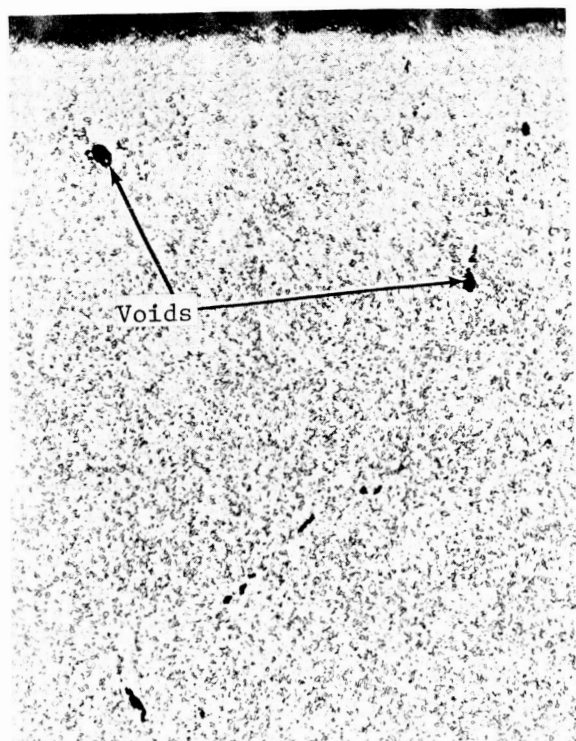
Post-Test Vapor Zone (A050221)

0 0.004
Inch

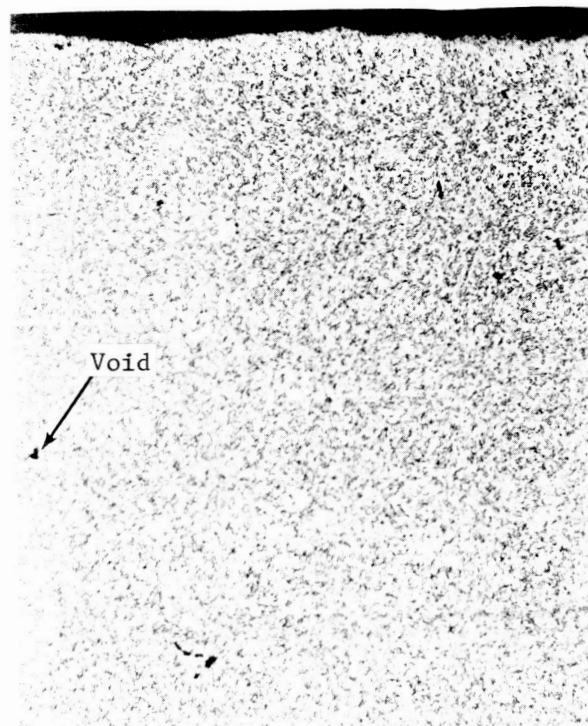


Pre-Test (A050111)

Figure 25. Microstructure of Zircoa 1027 (95.5ZrO_2) Before and After Exposure to Potassium Liquid and Vapor for 1000 Hours at 1600°F .
Etchant: Boiling $\text{H}_2\text{SO}_4 + \text{HF}$ Mag: 250X

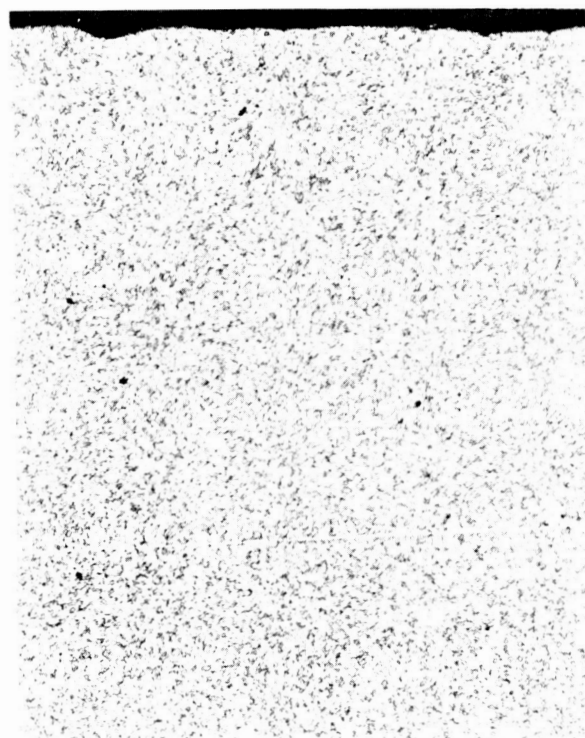


Post-Test Liquid Zone (A052721)



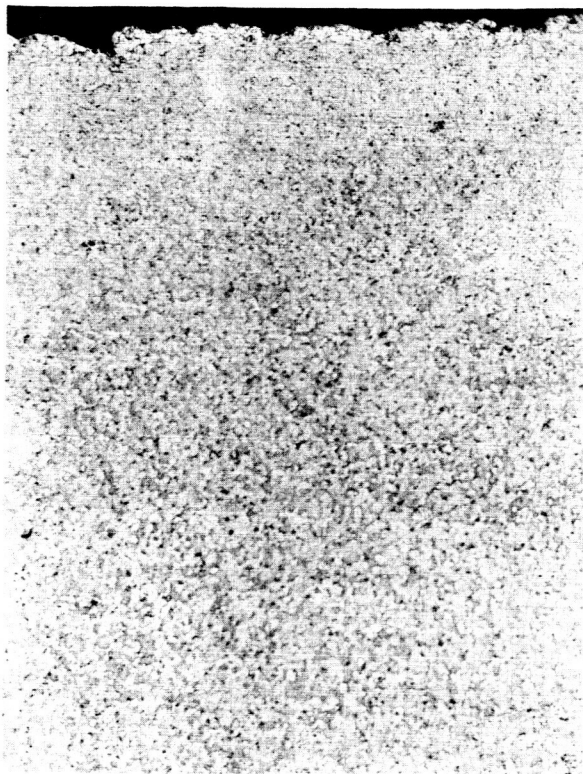
Post-Test Vapor Zone (A052821)

0 0.004
Inch

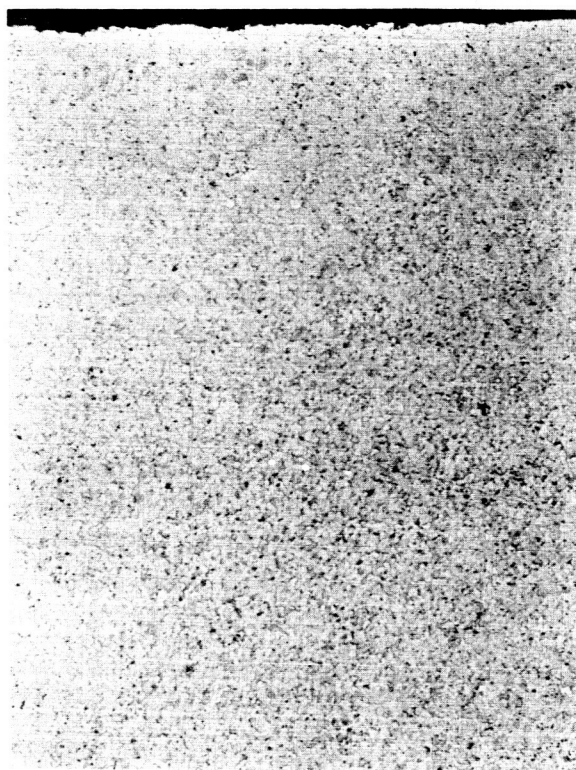


Pre-Test (A052711)

Figure 26. Microstructure of K601 (84.5%W-10%Ta-5.5%C) Before and After Exposure to Potassium Liquid and Vapor for 1000 Hours at 1600°F.
Etchant: 20% Murakamis Mag: 250X



Post-Test Liquid Zone (A051921)



Post-Test Vapor Zone (A052021)

0 0.004
Inch

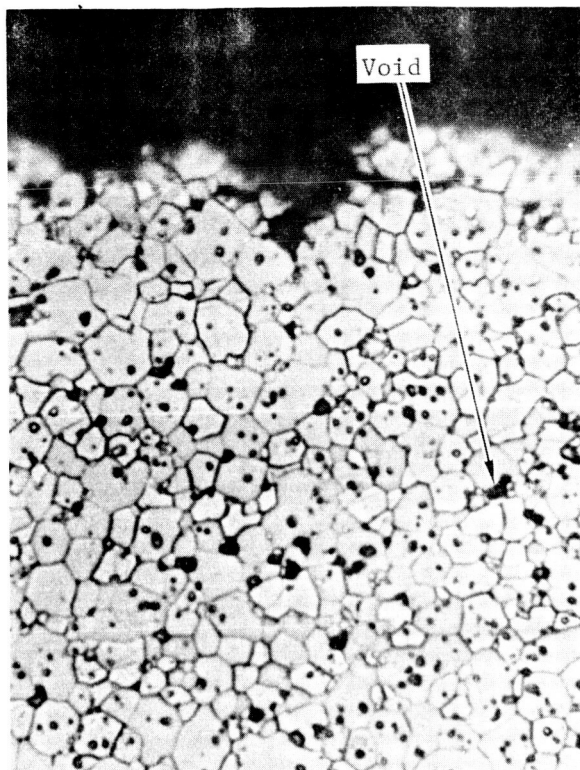


Pre-Test (A051911)

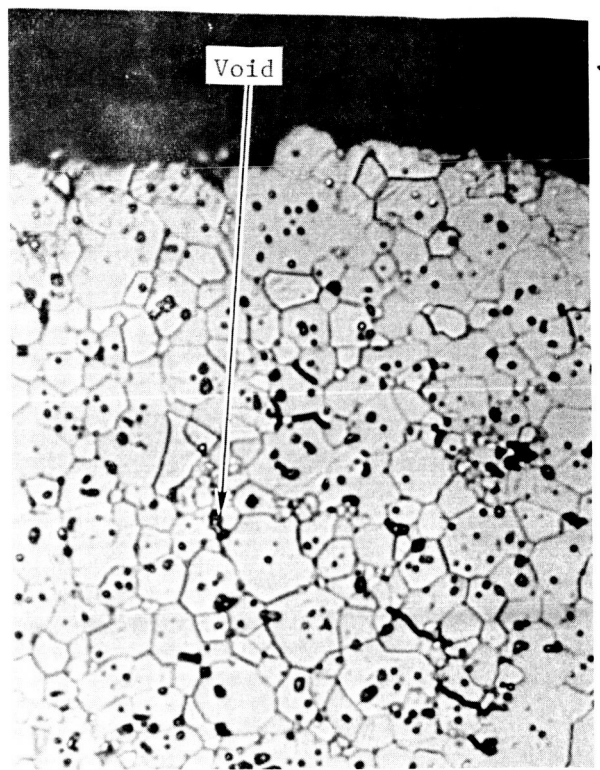
Figure 27. Microstructure of TiC Before and After Exposure to Potassium Liquid and Vapor for 1000 Hours at 1600°F.

Etchant: 80% HNO_3 +20% HF

Mag: 250X



Post-Test Liquid Zone (A051923)



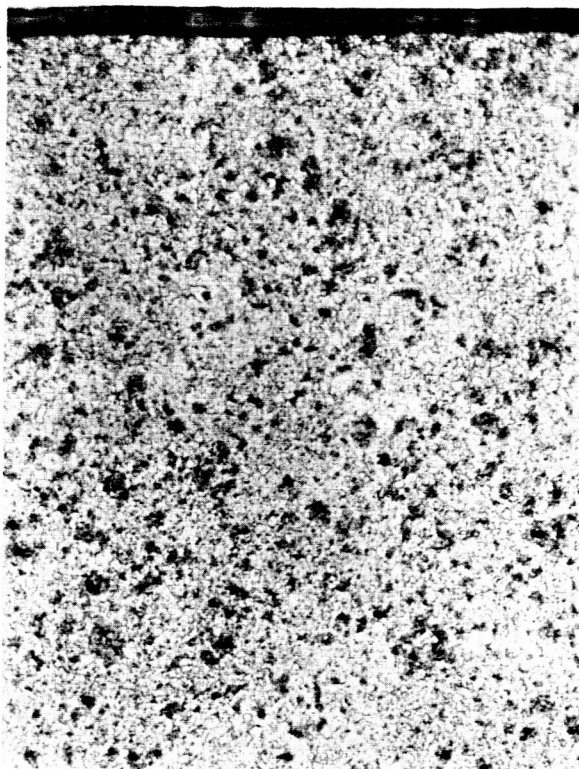
Post-Test Vapor Zone (A052023)

0 0.0005 0.001
Inch

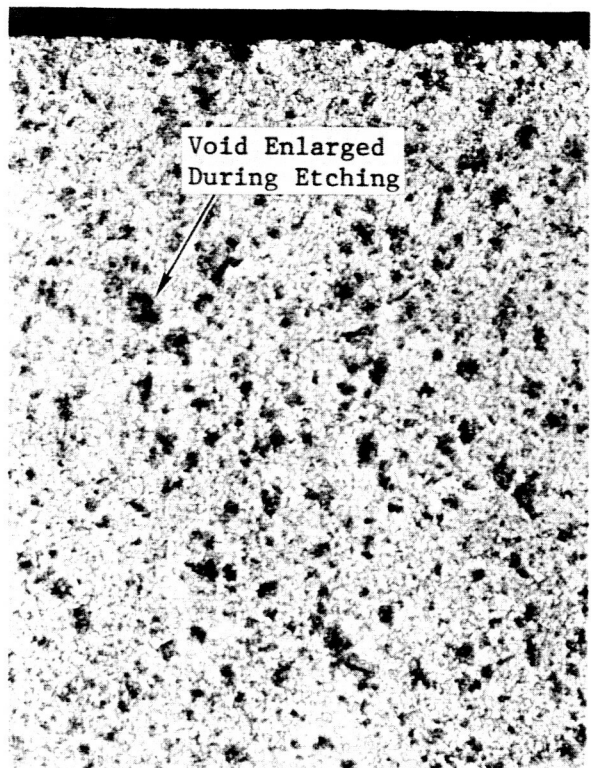


Pre-Test (A052013)

Figure 28. Microstructure of TiC Before and After Exposure to Potassium Liquid and Vapor for 1000 Hours at 1600°F.
Etchant: 80% HNO_3 +20% HF Mag: 2000X

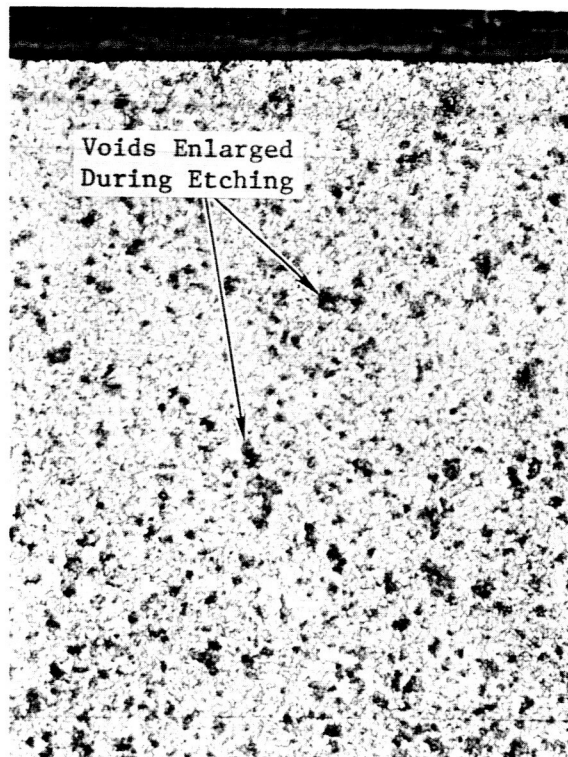


Post-Test Liquid Zone (A051521)



Post-Test Vapor Zone (A051621)

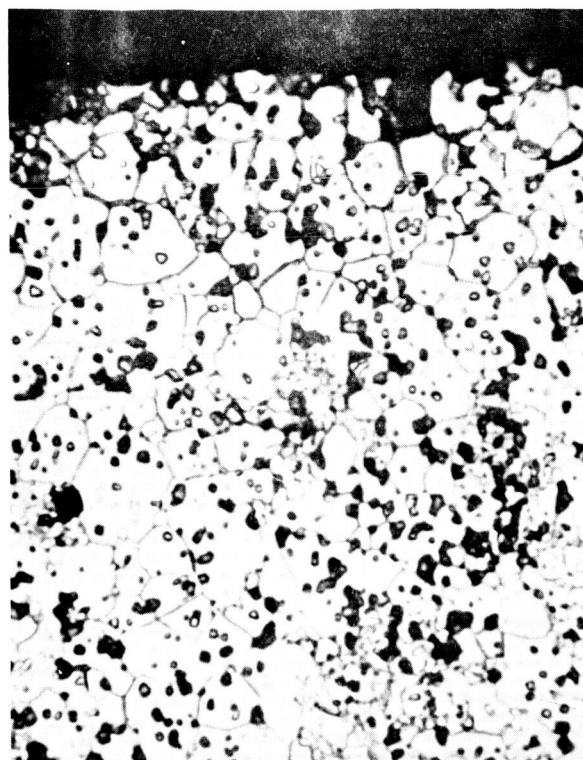
0 0.004
Inch



Pre-Test (A051511)

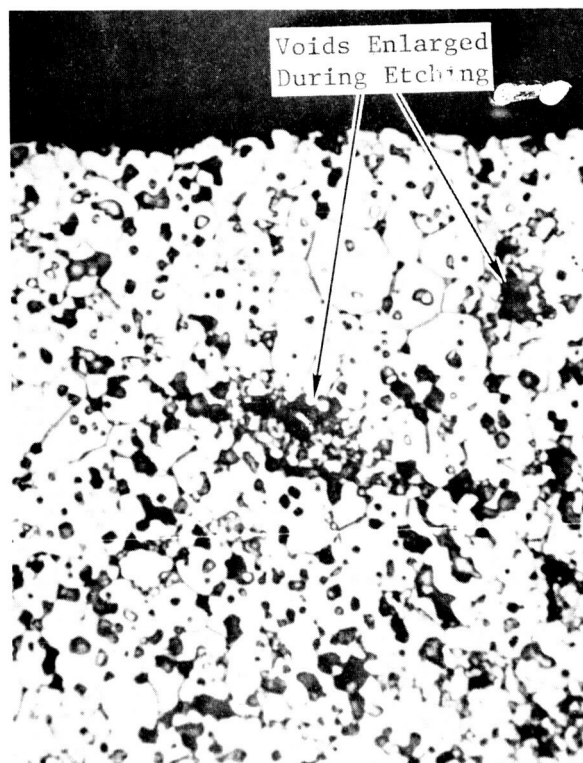
Figure 29. Microstructure of TiC+5%W Before and After Exposure to Potassium Liquid and Vapor for 1000 Hours at 1600°F.
Etchant: 80% HNO_3 +20%HF

Mag: 250X



Post-Test Liquid Zone (A051523)

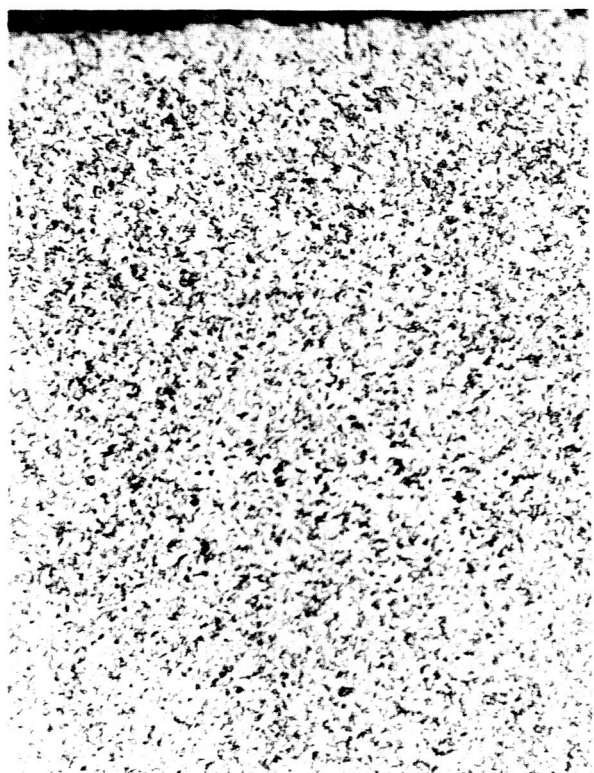
0 0.001
Inch



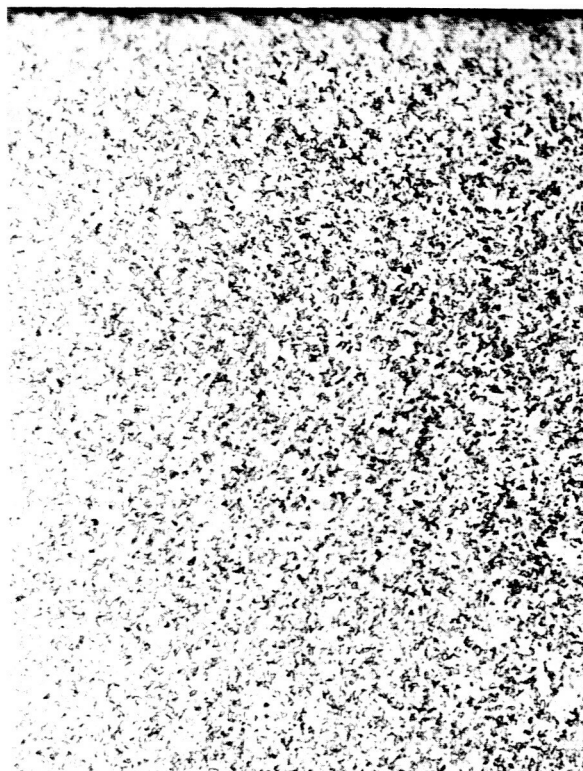
Pre-Test (A051513)

Figure 30. Microstructure of TiC+5%W Before and After Exposure to Potassium Liquid for 1000 Hours at 1600°F.
Etchant: 80% HNO_3 +20%HF

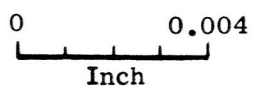
Mag: 2000X



Post-Test Liquid Zone (A050721)



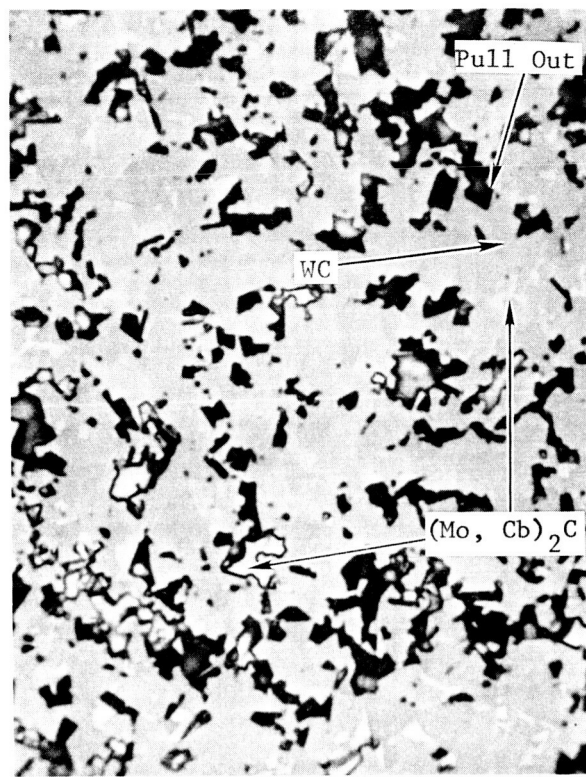
Post-Test Vapor Zone (A050821)



Pre-Test (A050711)

Figure 31. Microstructure of Grade 7178 (85.6%W-6.9%Mo-1.8%Cb-0.3%Ti-5.7%C) Before and After Exposure to Potassium Liquid and Vapor for 1000 Hours at 1600°F.
Etchant: 10%NaOH, Electrolytic

Mag: 250X



Post-Test Liquid Zone (A050724)

0 0.0005 0.001
Inch



Pre-Test (A050714)

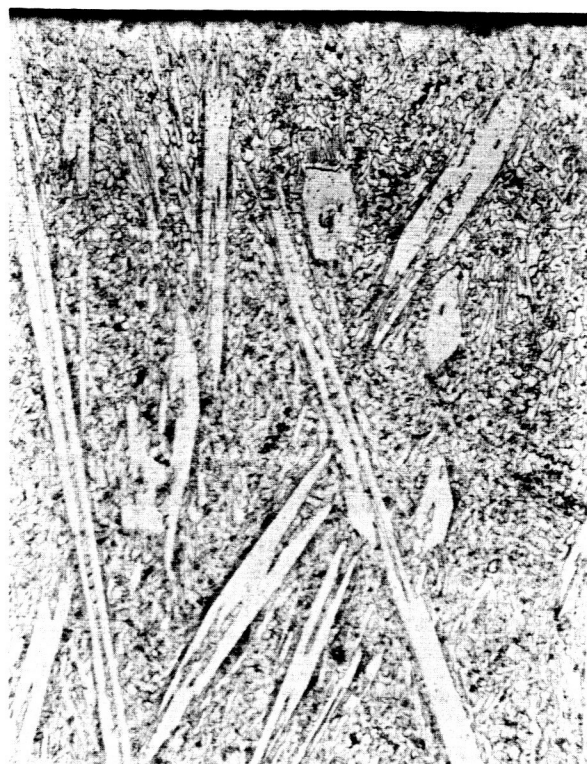
Figure 32. Microstructure of Grade 7178 (85.6%W-6.9%Mo-1.8%Cb-0.3%Ti-5.7%C) Before and After Exposure to Potassium Liquid for 1000 Hours at 1600°F.

Etchant: 10%NaOH, Electrolytic

Mag: 2000X



Post-Test Liquid Zone (A050521)



Post-Test Vapor Zone (A050621)

0 0.004
Inch

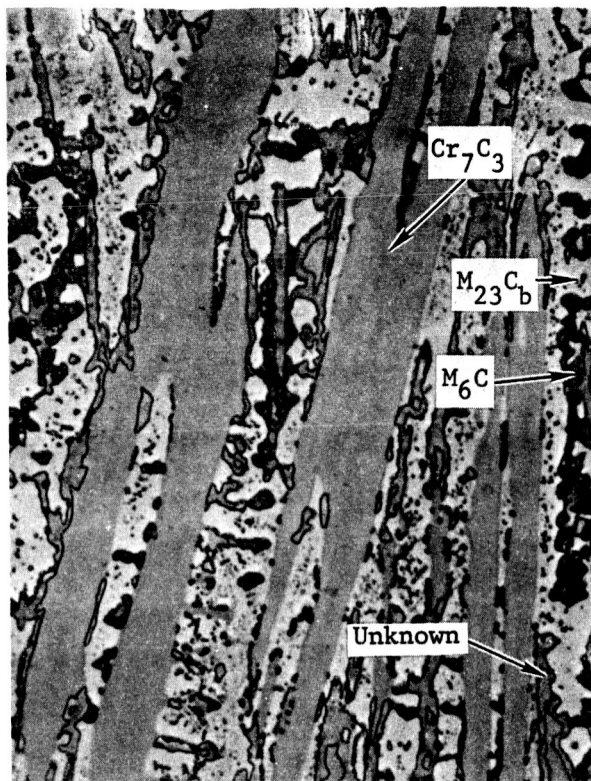


Pre-Test (A050511)

Figure 33. Microstructure of Star J (17%W-32%Cr-2.5%Ni-3%Fe-2.5%C-Bal Co) Alloy Before and After Exposure to Potassium Liquid and Vapor for 1000 Hours at 1600°F.

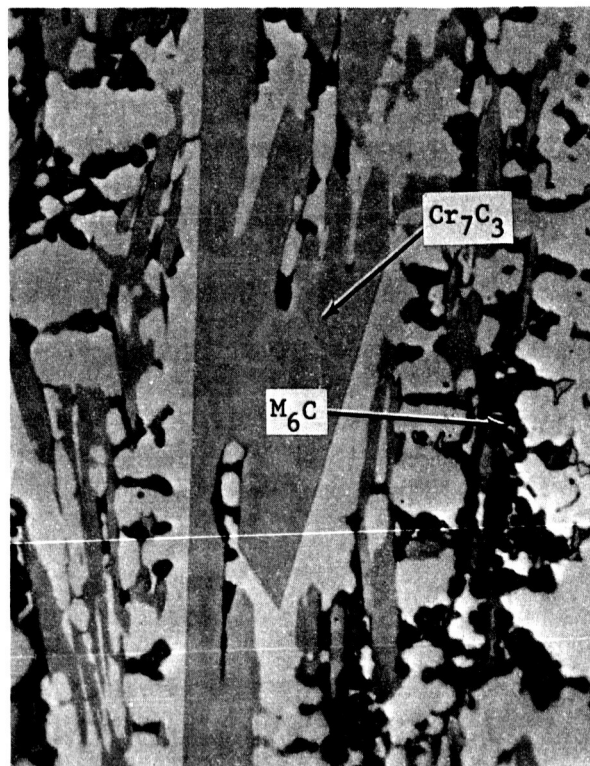
Etchant: 10% Oxalic Acid, Electrolytic

Mag: 250X



Post-Test Vapor Zone (A050622)

0 0.001
Inch



Pre-Test (A050611)

Figure 34. Microstructure of Star J (17%W-32%Cr-2.5%Ni-3%Fe-2.5%C-Bal Co) Alloy Before and After Exposure to Potassium Liquid for 1000 Hours at 1600°F.
Etchant: 2% Chromic Acid, Electrolytic + Grosbeck's Reagent
Mag: 1000X

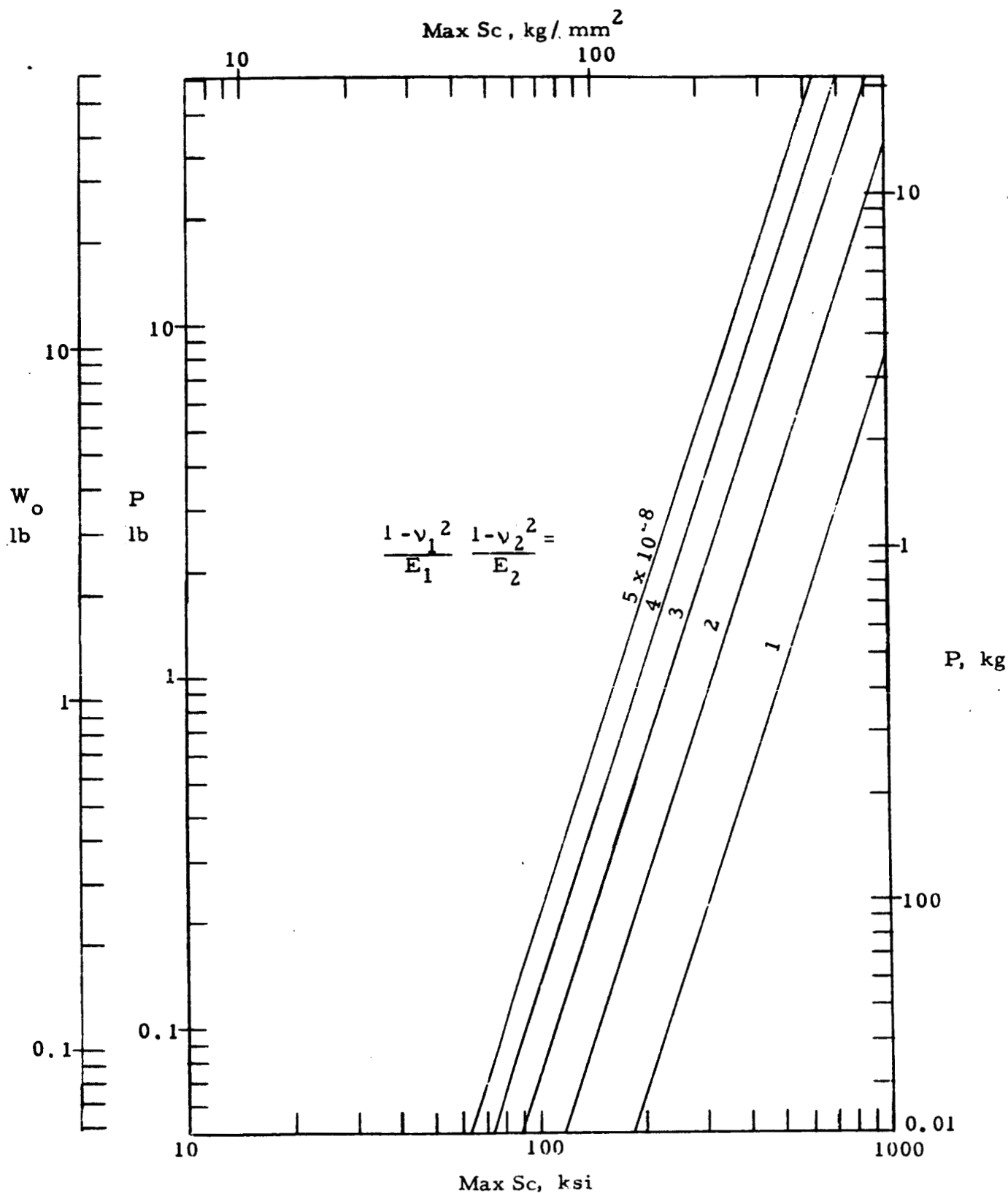


Figure 35. Curve for Calculation of Load to Produce Hertzian

Stress of (Max Sc) Between Sphere and Flat Surface;

$$P = \left(\frac{\text{Max Sc}}{0.918} \right)^3 D^2 \left[\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \right]^2$$

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